STEREO PIV DIAGNOSTICS OF SWIRLING PROPANE FLAMES

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ABSTRACT: Reacting flows are encountered in various industrial applications such as combustors, chemical reactors, etc. An investigation of the large-scale coherent vortical structures (LVS) impact on turbulent mixing and burning steadiness is the important task. LVS control in a flow is possible by external periodical excitation of inlet velocity and superimposition of swirl on a flow (e.g. Alekseenko et al., 2008). Main problems that arise during burning intensification due to improved fuel and air mixing are blow-off, a flash-back and appearance of a thermoacoustical resonance effects in a burning facility.

Stereo PIV diagnostics of reacting flows allows obtaining comprehensive data for assessment of a LVS impact on a behavior of a flame. PIV images for air flows are characterized by nonuniform particle image seeding density limiting standard cross-correlation PIV methods ability to image processing due to presence of outliers in low concentration areas. In this work the approach that allows effective outliers filtering during PIV processing is proposed. The signal filtering is performed during particle image preprocessing using information on the local particle image concentration. In combination with the adaptive sampling and windowing method proposed by Theunissen et al. (2007), this technique allows to get spatial distribution of statistical characteristics with good accuracy.

Flame front analysis was done through images from a high-speed Redlake camera operated at frame rate 200Hz in visible spectral region. Determination of the flame front was performed by the image segmentation. Together with Stereo PIV measurements this analysis was performed for the premixed combustion in the wide range of parameters: Reynolds number, swirling rate and equivalence ratio.

1 Introduction

The increasingly stringent environmental regulations promote the design of new combustors operating with minimum detrimental emissions. So far, lean premixing of fuel and air has the highest NOx-abatement potential of all known combustion technologies [1, 2]. Practical implementation of this technology is hindered by that the lean premixed (LP) flames are prone to combustion instabilities induced by various sources [3, 4]. One of the sources of this instability, limiting the range of the LP combustor operation, is the hydrodynamic flow unsteadiness superimposed by the large-scale coherent structures [5, 6, 7]. On the other hand, control of these structures (e.g., by acoustical forcing) may be
beneficial for the flame stabilization through the enhanced turbulent mixing, and thus can promote combustion efficiency [8].

Against this background the present work is devoted to the experimental study of premixed flame/flow regimes in different configurations. One of the tasks of this work is to define the appropriate PIV algorithm which is able to extract instant velocity fields from particle images with nonuniform seeding density. This algorithm should allow calculating second-order velocity moments from resulted instant velocity fields with reliable accuracy. Thus it has to effectively filter all velocity outliers. The central point of the analysis was done on a clarification of the role of coherent structures in the flame stabilization improvement. Important matter which was also explored is the possibility of controlling the combustion process, namely, enhancing the flame stability and reducing emissions, by modification of characteristics of the coherent structures by passive methods of control.

2 Experimental setup

The experimental circuit consisted of a burner, air fan, fuel (propane) tank, premixing chamber, section for air and fuel flowrate control (see Fig. 1).

![Combustion facility measurements system (a), sketch of contraction nozzle (b) and scheme of swirler arrangement (c)](image)

The burner represented a profiled contraction nozzle with a plenum chamber containing smoothing grids (see Fig. 1a). The nozzle was designed to provide a 'top-hat' velocity distribution at the nozzle exit for the non-swirling flow. In the most of the experiments, the nozzle exit diameter \( d \) was 15 mm and the area contraction rate was 18.8. Additionally, scale factor of the burner was varied by using profiled nozzles with the same shape but different exit diameters (8 and 10 mm).

For organization of the flows with mean swirl, the smoothing grids in the plenum chamber were replaced by a swirl generator (see Fig. 1b). The definition of the swirl rate was based on the swirler geometry [9]:

\[
S = \frac{2}{3} \left( \frac{1 - (d_1/d_2)^3}{1 - (d_1/d_2)^2} \right) \tan(\phi) \tag{1}
\]

Here, \( d_1 = 7 \) mm is the diameter of a centerbody supporting the blades, \( d_2 = 27 \) mm is the external diameter of the swirler, and \( \phi \) is the blade inclination angle. During the experiments, wide range of Re number was covered (from 500 to 8,000). The swirl rate \( S \) was varied from 0 to 1.0 by using swirlers with different blade angle. The geometry of the nozzle and swirlers was the same as in the study of the
water swirling turbulent (Re = 8,900) jets by [10]. The distributions of the initial velocity and values of swirl rate calculated from them can be found in it.

In the present work the combustion regimes were studied by means of flame visualization and direct measurements of instantaneous velocity fields in the flow. For the velocity measurements an advanced non-intrusive diagnostics tools, namely Stereo PIV, was used. Sketch of PIV system arrangement is shown in Fig. 1. The "PIV-IT" system consisted of a double cavity Nd:YAG pulsed laser with 70 mJ power per pulse, synchronizing processor, and a couple of CCD cameras (1360×1024 pixels, 10 bits) equipped with optical filters. The optical filters with narrow bandwidth (532±10 nm) were used to provide suppression of intense flame emission and to allow the camera to register mainly the seeding particles reflecting the laser light. A laser sheet was formed by a set of cylindrical and focusing lenses and had a minimal thickness of 0.5 mm in the measurement area. A specially designed flow seeding facility was used to provide PIV measurements. Oxide aluminum particles with diameters 1-3 µm were used for the flow seeding. According to [11] mentioned particle size is small enough to be able to neglect the velocity lag related to the particle inertial force, as well as the thermophoretic force in the nonisothermal flow.

During the experiments, the system was operated by a computer with "ActualFlow" software. In the present stereo configuration the angle between the optical axis of each camera and normal of the measurement plane was about 30°. The number of image pairs captured by each camera was 2,500. For calibration of the optical system during Stereo PIV experiment the translated flat calibration target 50x50 mm with the dot spacing 3 mm was used. Three images of the target located in different normal-to-plane positions were captured: {-1, 0, 1 mm}.  

3 Data processing
The following methods were used for experiment data processing:
• Digital filtering of PIV images and segmentation of chemiluminescence images;
• The adaptive 2DPIV algorithm with vectors filtration based on the local concentration of particles;
• The algorithm of the stereo reconstruction of velocity fields.

3.1 Image preprocessing
Images of particles in the reacting flow contain fields, where flame luminosity is seen, see Fig. 2a. Luminance reduces signal-to-noise ratio of the cross-correlation analysis of PIV images, thus background flash is not desirable effect. To eliminate the contamination by flame emission which passed thru the narrow-band optical filters, digital filtering of images was used. In Fig. 3b and c, the result of the application of two different nonlinear filters with a finite impulse response to the original image sample (Fig. 3a) is shown. The filter corresponding to Fig. 3b subtracts the sliding minimum value from the original pixel intensity value. One can see that the experimental images contain zero intensity pixels which are directly adjacent to bloomed pixels from brightest particles and the edge of the nozzle. The dark pixels with application of the sliding minimum filter create blocks of remained bright pixels with the size equal to the size of the filter kernel see Fig. 3b. Consequently, due to this effect the sliding minimum filter has not suited for data processing and it was changed by the more timeconsuming, but free from this undesired shortcoming, auxiliary sliding...
median filter. The result of the application of the auxiliary sliding median filter for the test image sample is shown in Fig. 3c.

Fig. 2 First frame particle image with 128x128 pix grid not filtered (a), filtered with high-pass filter - auxiliary to median 9x9 pix kernel (b); nozzle exit in the bottom of the image, the images are in an inverted color ($S = 1$, $d = 15$ mm, $Re = 4,000, \Phi = 3.4$)

Fig. 3 First frame particle image sample 128x128 pix from Fig. 2 not filtered (a), filtered with high-pass filter - auxiliary to minimum 15x15 pix kernel (b), filtered with high-pass filter - auxiliary to median 15x15 pix kernel (c); all the samples are in an inverted color

The size of the filter kernel affects its bandwidth. The larger the size of a kernel, the more low-frequency components of the signal remains in an image. For the image processing in the present work, the size of the filter kernel 9x9 pix was used. In Fig. 2b the result of digital filtering of a whole image is shown. It is seen that the filtering removes the flame light effect, flashes, formed by the reflection of light from the laser at the edge of the nozzle, and eliminates overexposed pixels.

Chemiluminescence images were obtained from the high-speed camera images and digital filtering of PIV images. In this case digital filtering was directed into suppression of particle scattering light and amplification of a flame luminosity by sliding median filter. Image segmentation of chemiluminescence images was performed by simple thresholding with further extraction of a flame luminosity contour. Flame contours were used in order to evaluate approximate location of a reacting zone.

3.2 PIV velocity field validation algorithm based on particle concentration
2D2C PIV adaptive algorithm is based on [13], which proposed to change the size and position of the interrogation area at the point of measurement, depending on the concentration of particles in a test window and the local level of velocity fluctuations. For the present experiment, only the flow coming from the nozzle was seeded by tracers, while the ambient air was not seeded. Thus, the PIV images had inhomogeneous particle concentration, which limited the possibility of cross-correlation methods for the processing of such images due to outliers in zones of low particle concentrations (see Fig. 4a, b). Due to iterative refinement of the velocity vector grid during the image processing the outliers grouped in clusters. This made difficult to use known methods of velocity fields filtration [14]. Besides, the outliers remained after post-processing of velocity fields severely impaired the quality of the statistical characteristics obtained from these velocity fields [15]. Especially it spoils turbulence intensity fields, as well as the higher-order velocity moments.

![Image](a) (b) (c)

Fig. 4 Couple of images (a), without analysis of particles per IW (b), with analysis of particles per IW (c) ($S = 0$, $d = 15$ mm, $Re = 2,400$, $\Phi = 0$)

Additional advantages of the method described in [13] except for improving accuracy and spatial resolution of measurements, which the authors focused on, are an efficient filtering 'possible' spurious vectors and reducing the computation time.

![Flowchart](image)

Fig. 5 Effective PIV velocity field validation algorithm based on particle concentration

Spurious vectors are 'possible' because in these measurement points they are actually not computed. But if they were calculated it is likely proved to be outliers. Thus, the filtration of the velocity field is performed by the image preprocessing. During preprocessing particle image concentration in the future measurement points is calculated (see block Particle detection $N(i,j)$ in Fig.)
5) and the exclusion from consideration of the points in which concentration of particles below the threshold \( x \) is done.

Reducing the time of calculation occurs at the expense of passes measuring points excluded from consideration. According to the results of testing on the air jet experiment data, the preprocessing time takes less than 5% of the velocity field calculation time and reduces up to 30% the time of the velocity field calculation itself. Reducing of the processing time occurs only in case when there are image areas with a low particle concentration and image areas with no particles at all. For this type of images created and implemented the described algorithm.

Identification of particles was done by Particle Mask Correlation (PMC) [16]. The size of the interrogation area \( WS(N(i,j)) \), see Fig. 5, had linear dependence on the concentration of particles \( N(i,j) \). Fig. 6 (a) shows how \( WS \) changed through the image depending on the local concentration of particles. Instant velocity field corresponding to the image is shown in Fig. 6 (b).

![Fig. 6 PIV particle images with (a) random selected positions of interrogation windows and their size (b) the instantaneous velocity field and the flame front presented by gray line (\( S = 0, d = 15 \) mm, \( Re = 2,400, \Phi = 0 \))](image)

One of the advantages of the described algorithm is the ability to use any appropriate PIV method for calculating of the velocity vector at the point of measurement: standard or adaptive cross-correlation with or without image deformation and etc.

### 3.3 Velocity stereo reconstruction algorithm

The location of measurement points in a target image was identified by a recognition algorithm with subpixel method of the center marker determination by correlating with a marker pattern. The camera model parameters were calculated for the central projection of the projective transformation (DLT) [17]. An alignment of a plane calibration target and a laser plane was carried out by the self-calibration method [18] for each regime individually using 100 particle image stereo pairs. The exact position of the calibration target was determined after convergence for 3-4 iterations of the self-calibration procedure. The out-of-plane calibration target misalignment was not greater than 0.3 mm.

The stereo reconstruction method based on local gradients of a mapping function proposed by [19] was utilized in this work. The algorithm has been added by accounting spurious vectors on reconstructed stereo velocity fields, which were transferred from projections of 2D2C velocity fields from both cameras into a resulting 2D3C velocity field. Also, 2D3C vectors filtration produced by a residual criterion of acceptable [17] from approximate solution of an over determined linear equation.
linking particle displacement in the measurement plane and the image plane. The residual value should be less than 0.5 pix.

4 Results

4.1 Visualization of flow regimes

Fig. 7a shows direct images of the flames at different Re-Φ conditions together with the blow-off curve obtained for the non-swirling flow (S = 0 and d = 15mm). The blow-off curve indicate the upper value of Re for the fixed Φ for which the flame still exists. For a greater Re the flame was blown away by the upstream flow. Also, the flame flash-back to the nozzle was observed for low Re numbers. However, study of the flash-back effect was not the aim of the present paper. Depending on Re and Φ values, various combustion regimes between an attached classical Bunsen flame and a remote from the nozzle 'lifted' flame were observed.

For the lean premixed flame (Φ = 0.95) at Re = 1,200 a distinct flame cone with a thin flame layer was observed. A lean combustion regime is the most interesting from the position of a low NOx emission. However, according to the blow-off curve one can conclude that the maximum Re number for the lean regimes is about 1500 for the present nozzle configuration. With Re and Φ increase along the blow-off curve, the flame separated from the nozzle and the 'lifted' flame regime was observed. The distance from the flame to the nozzle increased while moving along the curve. For a low Re number, increase of Φ resulted domination of diffusion combustion regime. The role of large-scale vortices in these regimes and the mean flow characteristics will be given in more details in the next section.

As it was already mentioned, the nozzles with d = 8 and 10 mm were tested besides the case of d = 15 mm. Fig. 8a shows the blow-off curves obtained for these diameters and also presents the curve obtained in [12] for the propane flame for d = 18 mm. Generally, increase of the nozzle diameter leads to a greater slope of the blow-off curve, and thus, to larger Re numbers for which the lean combustion exists. The maximum values for Φ = 1.0 were Re = 3,000 and 1,600 for d = 18 and 15 mm, respectively. It should be mentioned that for the case of d = 8 mm there was no cone observed at all.

Typical flame regimes for the swirling flow at S = 0.41 and d = 15 mm are presented in Fig. 7b together with the blow-off curve. It should be mentioned that for this nozzle configuration, there was no vortex breakdown and recirculation zone observed in the previous study [10] of the flow without reaction at Re = 8,900. For the flow with combustion studied in the present work, different flame regimes were observed. Examples of the stoich flames at the low (Φ = 1.04, Re = 980) and high (Φ = 1.15, Re = 7,400) Reynolds number are shown in Fig. 7b. In the first case the flame was found to be steady. Increase of Re number led to a growth of azimuthal instabilities in the flame layer and the flame became turbulent as it is shown in Fig. 7b for the Re = 7,400 case. For the relatively high Re and Φ numbers (around Re > 4,000 and Φ > 2), 'lifted' flame regimes were observed. Majority of regimes observed at Re-Φ diagram between laminar, lean and 'lifted' flames was the flame penetrating inside the nozzle forming a quasitubular flame structure (see Re = 3370 and Φ = 1.83 in Fig. 7b). For the non-reacting flow at S = 0.41 Re = 8,900 [10], intense helical vortices were observed near the jet axis core sponging locally great intensities of velocity fluctuations (up to 47% of the mean flowrate velocity). The flame front localization near the jet axis can be explained by this region of intense mixing.
Fig. 7 Re-\(\Phi\) diagram with blow-off curve and examples of typical flame regimes for \(d = 15\) mm and \(S = 0\) nozzle (a), Re-\(\Phi\) diagram with blow-off curve and examples of typical flame regimes for \(d = 15\) mm and \(S = 0.41\) nozzle (b)

Fig. 8 Blow-off curves for different nozzle diameters. \(d = 18\) mm case is from Fernandes and Leandro (2006) (a), Blow-off curves for different nozzle diameters, \(d = 15\) mm (b)

Fig. 9 shows Re-\(\Phi\) diagram for the swirling flow at \(S = 1.0\). For this swirl rate, a clear vortex breakdown with a large recirculation zone near the nozzle exit was observed in the previous study of the flow without reaction [10]. Intensities of velocity fluctuations were found to reach greatest values (near 50% of the mean flowrate velocity) in the inner mixing layer and were about 3.7 times greater than for the jet at \(S = 0\) in the mixing layer. The recirculation zone with large helical vortices is expected to be responsible for great values of Re for the lean combustion in comparison to the non-swirling flow. For the flow with combustion, various flame regimes were observed depending on Re and \(\Phi\). For example, the 'lifted' flame regime was for \(\Phi = 6.9\), Re = 2,000 and combustion regime with outer and inner flame layer (similar to the \(\Phi = 1.34\), Re = 980 case for \(S = 0.41\)) was at \(\Phi = 3.5\), Re = 1,000 with strong helical dominating in the outer layer (these regimes are not shown in Fig. 6). Similarly to the \(S = 0.41\) case, lean premixed and quasitubular flame regimes were observed as well.
The blow-off curves obtained in the present work for $d = 15$ mm $S = 0$, 0.41 and 1.0 are shown in Fig. 8b. Introduction of a swirl results in a greater slope of the blow-off curve, and thus, to larger Re numbers for lean premixed flame stable operation in comparison to the non-swirling flow. For both $S = 0.41$ and 1.0 cases, shape of the blow-off curve and the observed turbulent regimes were quite similar. The upper limits of Re number for $\Phi = 1.0$ are as follows: Re = 1,600 for $S = 0$, Re = 4,500 for $S = 0.41$, and Re = 7,400 for $S = 1.0$ cases, respectively.

### 4.2 Stereo PIV measurements

This section provides results of PIV measurements in the jet flame at $d = 15$ mm. Also, several flows without combustion were tested and were compared to the flames at the similar conditions. On the first stage the influence of the seeding particles on the flame regime was tested. No significant difference in flow regimes depending on Re and $\Phi$ was found between seeded and not seeded flow. Only the region of the flame blow-off shifted towards greater Re numbers in the latter case.

Fig. 10 shows an example of the normalized average velocity for the jet at $S = 0$ and Re = 2,000, $\Phi = 1.1$. Flow velocity inside the cone is $U_0 = 2.27$ m/s. Increase of gas velocity up to 3.01 m/s (133\%) after passing through the flame front due to the buoyancy effect is clearly seen. According to the cone inclination angle $\alpha$ (relatively to the jet axis) and the mean flowrate velocity, the laminar flame velocity is $U_f = U_0 \sin \alpha = 0.45$ m/s directed normal to the front. In Fig. 10b spatial distribution of the azimuthal component of the mean flow velocity is shown with magnitude of 0.1 $U_0$ which corresponds to the 3.5\% of measurement uncertainty. Measurement uncertainty inside the flame cone is lesser than 1\%. Dashed black line in Fig. 10 and all figures below means rough (or average) position of the flame front extracted from chemiluminescence images.

The time-averaged velocity field for the 'lifted' turbulent flame in comparison to the cold flow is shown in Fig. 11. One can observed that there is no essential difference in the mean velocity distributions for $z/d < 1.3$. However, far downstream the flow with combustion has a fast increase of the jet spreading rate. The vector field shows the tendency of the flame to deflect the flow due the flow...
acceleration when it passes through the flame layer. The flame front represented bottom of a torus with a sharp temperature gradient.

![Fig. 10 Spatial distribution of normalized mean velocity for flow at $S = 0$, $d = 15$ mm, $Re = 2,000$, and $\Phi = 1.1$, (a) in-plane velocity components, (b) out-of-plane velocity component](image1)

![Fig. 11 Spatial distributions of normalized mean in-plane velocity components for flow at $S = 0$, $d = 15$ mm, and $Re = 4,000$; (a) cold flow, (b) lifted flame at $\Phi = 2.8$](image2)

Influence of the combustion for the 'lifted' flame regime on turbulent statistics is demonstrated in Fig. 12. Two cases at the similar parameters are compared and the axial component of the turbulent kinetic energy (TKE) is shown as an example. For the case without combustion, monotonous growth of $\langle u^2 \rangle$ was observed in the jet mixing layer. In case of the combustion, turbulent intensities were found to be greater in the initial region of the jet, before the flame front, and became suppressed when the flow passed through the flame layer. This reflects observations on vortices magnitude suppression made from the instantaneous velocity fields. Also, it is considered that the flame/vortex interaction in the region of flame stabilization produced pressure waves forcing instability waves in the initial shear layer of the jet that resulted faster growth of $\langle u^2 \rangle$ in comparison to the cold flow. In Fig. 12b the spatial distribution of the axial component of turbulent kinetic energy obtained by the conventional PIV algorithm without validation based on local particle concentration is shown for comparison. It is seen that in the right-hand area which corresponds to a low particle density value of velocity fluctuations is great due to the velocity outliers. Result in Fig. 12a obtained by proposed algorithm is free from this effect.
Fig. 12 Spatial distributions of axial component of turbulent kinetic energy for flow at $S = 0$, $d = 15$ mm, and $Re = 4,000$. (a) cold flow with validation algorithm based on particle concentration, (b) cold flow without validation algorithm, (c) lifted flame at $\Phi = 2.8$ with validation algorithm

Fig. 13 Radial profiles (a) of normalized mean velocity axial component and (b) normalized velocity fluctuation of axial component for cold flow at $S = 0$, $d = 15$ mm, $Re = 4,000$ and the same flow for lifted flame at $\Phi = 2.8$

Fig. 13 presents described behavior in the form of velocity profiles.

Fig. 14a, Fig. 15a, c shows spatial distributions of the mean flow velocity and axial component of TKE for the swirling 'lifted' flame at $S = 1.0$, $d = 15$ mm, $Re = 4,000$ and $\Phi = 3.4$. The distributions were not found to significantly differ from the previous study of the isothermal water jet at $Re = 8,900$, where high values of TKE were measured for $z/d < 0.6$. It is concluded that intense turbulent mixing at the initial region provides stabilization of the flame for the present parameters. The dashed red line in Fig. 14a, Fig. 15a, c indicates the recirculation bubble location.
Fig. 14 Spatial distributions of normalized mean in-plane velocity components for flows at $S = 1$, $d = 15$ mm (a) lifted flame at $Re = 4,000$, $\Phi = 3.4$, (b) premixed flame at $Re = 6,800$, $\Phi = 0.95$

Fig. 15 Spatial distribution of normalized mean out-of-plane velocity component and axial component of turbulent kinetic energy for flows at $S = 1$, $d = 15$ mm (a, c) lifted flame at $Re = 4,000$, $\Phi = 3.4$, (b, d) premixed flame at $Re = 6,800$, $\Phi = 0.95$
Stoich combustion regime for the same nozzle geometry, but at the different parameters (Re = 6,800 and Φ = 0.95) was found to have significantly different distributions (see Fig. 14b, Fig. 15b, d) from the previous case. The recirculation zone was less pronounced, i.e. negative axial velocity at the jet axis had significantly lesser absolute values. Spatial distributions of TKE components also had low values inside the recirculation zone. It was observed the turbulent pulsation were great only close to the flame layer up to z/d = 1.5 The great difference between the distribution of the mean velocity for the 'lifted' and stoich combustion regimes can be explained by the buoyancy effects. [21] have showed that the state (shape) of the vortex breakdown for the low-Re-number swirling jet is rather sensitive to the buoyancy effects. Conical or bubble regimes were observed depending temperature difference between the jet core and its surrounding fluid.

5 Conclusions
The present work reports results of the experimental study of premixed swirling jet flames at a wide range of Reynolds numbers, equivalence ratios and swirl rates. It is demonstrated that the application of the mean swirl to the flow is the most effective way to increase the range of Re numbers for steady lean combustion. Depending on the parameters, various combustion regimes were observed. For the most interesting cases of the turbulent combustion PIV measurements were performed.

The effective preprocessing velocity validation method based on local particle image concentration similar to the adaptive sampling and windowing 2DPIV algorithm [13] was used for processing of PIV images. It allowed extracting velocity fluctuation for inhomogeneous seeded PIV images of air flow. Besides that, the processing time was reduced by 30% with an application of this method by omitting interrogation areas with low particle concentration.

Spatial distributions of the mean velocity, turbulent kinetic energy were measured. Generally, it can be concluded that turbulence fluctuations become suppressed when the flow passes through the flame layer, but the flame itself is localized near the regions of high turbulent intensities and, consequently high turbulent mixing rate. Besides, comparison of the turbulence statistics for the flows with and without combustion showed that the flame/vortex interaction partially support the flame stabilization by a feed-back effect.

In the near future, the current experimental work will be extended to time-resolved PIV measurements with simultaneous tracking of the flame front and velocity fluctuations. Also the impact of the small-amplitude acoustical external periodical excitation of inlet velocity on the dynamics of the swirling reacting flow will be studied.

References


**6 Movies**

Movie 1: 2D3C instantaneous velocity fields for flow at $S = 1.0$, $d = 15$ mm, 'lifted' flame at $Re = 4,000$, $\Phi = 3.4$. Frame rate is 2Hz

Movie 2: Flame visualization with image segmentation for flow at $S = 0.41$, $d = 15$ mm, premixed flame at $Re = 1,885$, $\Phi = 1.31$. Images were obtained by a high-speed camera at 200Hz.

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