PIV/OH PLIF investigation of flow and flame front dynamics of acoustically perturbed conical flame

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Abstract. The paper reports on the investigation of the flow and flame front dynamics in a premixed conical methane/air flame perturbed by an acoustic field. The investigation is carried out by using stereoscopic particle image velocimetry and planar laser-induced fluorescence of HCHO to measure simultaneously the instantaneous velocity field and flame front location in the axial plane. The optical techniques provided information about local velocity and velocity gradients, stretching and curvature of the flame front. Flow conditions when the flame is covered from the top by a cooled metallic flat plate are also considered. It is found that the flow and flame front lose axial symmetry when the obstacle is present because of disruption of the global instability mechanism of the combustion products plume driven by bouncy force.

1. Introduction

Impinging flames, viz., jet-flames which flow against a solid obstacle, are studied because for some conditions self-induced instabilities may arise [1]. This feature allows to analyze thermoacoustic combustion phenomenon for well controlled conditions [2]. Planar laser-induced fluorescence (PLIF) is widely used for analysis of the local flame front shape, local gas temperature, species concentration (such as OH and NO) and heat release [3]. Such experimental data are very useful for better understanding of combustion processes. Accurate temperature and concentration measurements are also necessary for validation of theoretical models and numerical codes. Particle image velocimetry (PIV) method is now a standard tool for measurements in non-reacting flows [4] and often used for diagnostics of flows with combustion [5]. The advantages of the PIV method for reacting flows are almost negligible intrusiveness and possibility to measure instantaneous velocity field and estimate the velocity gradient. The latter feature allows to detect coherent flow structures, such as large-scale vortices.

In the present study an experimental investigation of flow and flame front dynamics was carried out for laminar impinging methane/air flame by using PIV and HCHO PLIF. To analyse unsteady behaviour of the flow/flame system, an external acoustic perturbations were imposed.

2. Experimental setup

The measurements were carried out for the methane/air flames at atmospheric pressure. The flames were organized in an open combustion rig (see details in [6]) by using a contraction axisymmetric
nozzle with the inner diameter at the outlet of $d = 15$ mm. The equivalence ratio $\phi$ of methane/air mixture issued from the nozzle was 0.7. The jet Reynolds number was fixed as 1700 (bulk velocity of the mixture was $U_0 = 1.7$ m/s). A metallic plate with diameter 80 mm, cooled by a recirculating water flow with temperature of 53°C, was placed normally to the jet axis for organization of the impinging flows. External perturbations of the flow/flame were provided by a loudspeaker, oriented radially to the nozzle rim at the distance 20 cm. The loudspeaker was connected to an amplifier, harmonic function generator, and electric power meter. The electric power supplied the loudspeaker was approximately 3W.

A photograph of the experimental setup is shown in the Figure 1. To provide PIV measurements, the flow issued from the nozzle was seeded by 4 μm TiO$_2$ particles. The surrounding air was seeded by using a fog generator. A pair of PIV cameras was mounted as shown in Figure 1. The used ImperX IGV-B2020 CCD cameras were oriented horizontally. The cameras were equipped with Sigma AF #50 lenses and band-pass optical filters (60% transmittance at 532 nm and full width of 10 nm at the half maximum). The seeding particles were illuminated by the second harmonic of a Nd:YAG laser with 200 mJ energy per each pulse. The laser beam was converted into the laser sheet with the use of a system of cylindrical and spherical lenses. Each camera captured 4 Mpix images. The time separation between two laser pulses was 40 μs.

For each flow case, 1000 instantaneous three-component velocity fields were measured. The PIV velocity fields were calculated by an in-house ActualFlow software with an iterative cross-correlation algorithm with continuous shift and deformation of the interrogation areas. Final size of the interrogation area for each velocity vector was equal to $32 \times 32$ pixels. Spatial overlap rate between the neighbour interrogation areas was 50%. The used cross-correlation algorithm accounted for the number of tracer particles in each interrogation area. If the number of particles was less than five, the velocity vector in this spatial domain was not calculated.

For the PLIF measurements radiation of the third harmonic (355nm) of a Nd:YAG laser (Quantel Brilliant B with 45 mJ energy per each pulse) was used to excite HCHO fluorescence. RMS of the pulses energy variation was below 5%. After the collimator optics, the height of the light sheet was 50 mm. The thickness of laser sheet was below 0.8 mm in the measurement region. Laser sheet
illuminated the axial plane of the reacting flow. The fluorescence of HCHO radicals was collected by a registration system consisted of an image intensifier (LaVision IRO) and sCMOS camera (LaVision, Imager sCMOS, 16 bit, resolution 2560×2160 pixel), equipped with a Sigma AF #50 lens and appropriate band-pass optical filter. The IRO photocathode (S20 multialkali) provided quantum efficiency about 25% for wavelengths in the range of interest. The exposure time for each image was 200 ns.

The raw PLIF images were processed by LaVision FlameMaster software to account for non-uniform spatial distribution of the laser sheet intensity, non-uniform spatial sensitivity of the registration system. Background signal and dark current were removed to sufficient extent by using PLIF images captured without combustion. In addition, an in-house image processing algorithm was used to determine local curvature of the flame front. The algorithm was based on the intensity gradient of the HCHO signal for determination of the flame front location. Local flame shape was approximated by the using Fourier series.

![Figure 2. Amplitude of the pressure waves passed through the gas supply path of the combustion rig](image)

To investigate resonance characteristics of the combustion rig for different distances between the nozzle and flat plate (H) a precision microphone Type 2250 by Bruel & Kjaer was used. Intensity of the pressure pulsations at the nozzle outlet was measured under conditions of superimposed external harmonic pressure oscillations (with frequency \( f_e \)) in the supply path. The results are shown in Figure 2. The resonance frequencies of the combustion rig (pipelines) are 160, 290, 395 Hz. The frequencies are the same for the configurations with and without the impingement surface, but the amplitude is lower in the latter cases.

3. Results

Figure 3 shows spatial distributions of the time-averaged velocity field for the reacting flows with and without the impingement plate. The contraction nozzle produced nearly “top-hat” velocity profile at the outlet. Thus, the velocity in inside the cone was almost uniform. Velocity of the gas passed through the flame cone increased due to the combustion, local heat release, temperature rise and density decrease. The impingement surface blocked the axial flow and produced flow in the radial direction.
Figure 3. Average velocity field for conical flames (left) without impingement surface and (right) with impingement surface for $H/d = 2$

Figure 4. Examples of the instantaneous velocity field for acoustically perturbed conical flames (left) without impingement surface and (right) with impingement surface for $H/d = 2$. White lines correspond flame front location detected from HCHO PLIF data.

Figure 5. Examples of approximation of the local flame shape. Dark-blue crosses shows coordinates of the pixels from HCHO PLIF data and red lines show result of approximation by smooth curves based on decompositions by Fourier series.
Figure 4 shows the instantaneous velocity snapshots for the region of flame front. The flame front cross-cut is visualized by white solid lines, determined from local intensity of HCHO signal, appeared at the preheat zone of the flame front. The external acoustic field resulted in oscillations of the jet flow issued from the nozzle and deformations of the flame front. Moreover, for the case of the impinging flow, the flame front and flow are clearly not symmetric.

To quantify flame front deformations (for the considered 2D data), a local flame front curvature was evaluated. This was done by evaluating coordinates \( x \) and \( y \) of each \( n \)-th pixel at the digitized boundary of the flame front. Figure 5 shows coordinates of the pixel and approximation by smooth curves based on decompositions by Fourier series. The local curvature \( k \) was evaluated according to the following equation:

\[
k = \frac{x'y'' - x''y'}{(x'^2 + y'^2)^{3/2}},
\]

where prime indicates derivation with respect to \( n \). The examples of the curvature evaluation are shown in Figure 6. The maximum of the curvature reached maximum at the flame front tip and corresponded to typical curvature radius of 0.1 mm.

**Figure 6.** Flame front curvature along the conical flames (left) without impingement surface and (right) with impingement surface for \( H/d = 2 \)

### 4. Conclusions

Experimental investigation of the flow and flame front dynamics in a premixed conical methane/air flame perturbed by an acoustic field was performed by using the stereoscopic particle image velocimetry and planar laser-induced fluorescence techniques. Two flow/flame conditions are considered, viz., open flame and flame blocked from the top by a flat cooled metallic surface. The instantaneous velocity field was measured in the axial plane simultaneously with detection of the flame front location. The optical techniques provided information about local velocity and velocity gradients, stretching and curvature of the flame front. The external acoustic field was superimposed to promote oscillations of the jet flow issued from the nozzle and deformations of the flame front. The flame from curvature reached maximum (approximately 10 mm\(^{-1}\)) at the flame front tip.
**Acknowledgments**

Financial support has been obtained from Russian Science Foundation (grant № 16-19-10566). A.S. Lobasov and V.M. Dulin are acknowledged for their assistance during the data processing and manuscript editing.

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