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SIMULTANEOUS IMAGING OF OH AND FORMALDEHYDE OF SUPERSONIC ETHYLENE JET FLAMES IN A HOT COFLOW

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Main subjects: OH, formaldehyde, simultaneous imaging
Fluid: sonic jet flame, hot coflow
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ABSTRACT: *The laser diagnostics system is built to acquire the single-shot images of OH and formaldehyde (CH_2O) and the temperature distribution. A sonic nonpremixed ethylene jet flames with hot coflow are measured and studied, and some results about simultaneous OH and formaldehyde images are acquired by calibration and post-procession, and which are comparing to CFD results. The flame structures, flow field and concentration distributions of radicals in sonic ethylene jet flames are measured and presented to indicate the mechanism between combustion reaction and high speed turbulent flow. The simultaneous single-shot results help to understand the interaction between turbulence and combustion. It seems the mismatch of two type images cannot be ignored, and then this error will influence the accuracy of the heat release rate calculation. Therefore, the methods and skills for multispecies PLIF and other simultaneous measurement need to be deal carefully.*

1 General Introduction

Laser-diagnostic techniques have been playing an increasing role in combustion research over the last 20 to 30 years. These techniques are attractive flow-measurement technique for detecting temperatures, flow fields and some special species or radicals concentration in combustion, because they are nonintrusive and robust.

Laser induced fluorescence (LIF) is probably the most commonly and important method to measure the densities of some minor species and radicals such as OH, CH, NO, and CO. Especially, planar laser induced fluorescence (PLIF) is more popular due to the high sensitivity, high temporal and spatial resolution. Laser Rayleigh scattering is commonly employed for temperature measurement in combustion. And imaging of the Rayleigh scattering signal is useful to map the temperature distribution of a chip in a flow illuminated by a laser sheet.

In the past decades, much works were aimed at the visualization of the structures of flame and flow field. OH is the popular specie which is measured using laser induced fluorescence method in most works because of its high concentration in flame and important part in the combustion reaction. The flame front positions could be acquired by processing the OH images.

Whereas OH-LIF is frequently applied for measurements in different flames, more details in combustion reaction paths and consumption rates of fuel cannot be given only from OH-LIF imaging. In general, quite a few intermediates have been investigated with PLIF in the past. Some radicals such as CH and HCO, which exist only in a very narrow region of the reaction zone due to their short lifetimes, are more suitable to indicate the flame front than OH. Other important investigations have indicated that the distribution of HCO correlates well with peak heat release rates for premixed flames [2, 3]. However single-shot LIF imaging of HCO is not easy to get, only few group have some experience about HCO-PLIF using special laser equipment [4, 5].

Instead, the distribution of OH and formaldehyde (CH_2O) is directly proportional to the reaction rate of CH_2O+OH →H_2O+HCO, which was showed in the Paul's work [3]. Further the formaldehyde (CH_2O) intermediate species is an important indicator of preheated zone in flame. The key point is the fluorescence signal of CH_2O is can be excited using 355nm laser, a typical laser wavelength. For investigate the flame structure simultaneous LIF imaging of OH and CH_2O were more and more frequently used in combustion research field [6-9].

In any turbulent flame, each instantaneous realization is different, and none is identical to the average. Therefore, a lot of effort has been put into the development of experimental methods enabling simultaneous imaging of two or even more species, or one intermediate and the temperature or velocity field [10-17]. The combinations of techniques that are both temporally and spatially resolved and allow simultaneous measurement of multiple quantities are in need for understanding the complex turbulent combustion flow and the validation of CFD works.

Some efforts and remarkable progresses on the technique of multi-species PLIF and temperature measurement simultaneously have been achieve by some groups[19-21], but getting stronger signal and improving the accuracy with higher spatial resolution remain lots of scientific and technical challenges. The current project aims to develop some techniques and build the laser equipment setup for measurement and visualization of multi species and temperature.

In this paper we report on the experiment work for a sonic ethylene jet in hot coflow, and the laser diagnostics system is built to acquire the single-shot images of OH and formaldehyde and the temperature distribution. Some results about simultaneous OH and formaldehyde images are acquired by calibration and post-procession, and which are comparing to CFD results. Comparisons are made between different fuel jet velocities and Reynolds number. Measurements are taken at two downstream locations. Based on these, a typical sonic ethylene jet flame with a heated and highly diluted coflow is realized and understood deeply.

2 Apparatus and methods

2.1 Experimental apparatus

A homemade turbulence burner with inner supersonic jet and hot coflow was designed and used in this work. This burner consists of a central sonic nozzle with a diameter of 1 mm, surrounded by a 250-mm hot coflow resulted from a rich premixed ethylene/air flame, which referred to the "Sydney burners" [14, 22] (see Fig. 1).

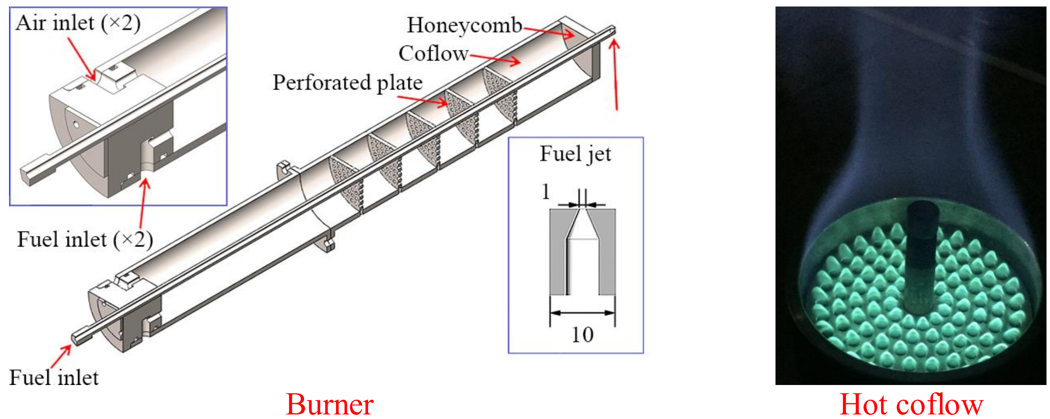


Fig. 1. Supersonic jet flame and hot coflow

The velocity of the coflow was kept constant at 1.5m/s and the equivalence ratio (ϕ) of the ethylene/air mixture is fixed to 0.48. The detailed parameters for temperature and species mass fraction of coflow for this work are listed in Table 1. The volume fraction of the residual O_2 is about 12%, which is used as the oxidizer of the jet flame. The supersonic nozzle injects the pure ethylene into the coflow with the injection pressure varying from 1.2 atm to 4.2 atm, which correspond to different velocities and Reynolds numbers, as summarized in Table 2. An injection pressure of 1.8 atm yields a jet velocity of 313 m/s, equaling to sound velocity in air, thus the Mach number equals to 1 in this case. The total temperature of ethylene was fixed at 300 K for all experiments.

Table 1 Temperature and species mass fraction of coflow.

Coflow ϕ	T/K	O_2 %	H_2O %	N_2 %	CO_2 %
0.48	1560	12	4	74	10

Table 2 Experimental conditions.

Cases	Case1	Case2	Case3	Case4	Case5
P (atm)	1.2	1.8	2.6	3.4	4.2
Max U (m/s)	170	313	407	466	501
Max Re	22210	40893	53174	60886	65455

2.2 Laser induced fluorescence for OH and CH_2O

A strategy for acquiring the spatial distribution of the hydroxyl radical (OH), formaldehyde (CH_2O) simultaneously has been studied. The laser diagnostic technique of multi-species planar laser-induced fluorescence has been developed and the experimental instruments, laser systems and cameras has been integrated for achieving the detail information of the turbulent flame.

Planar laser-induced fluorescence (LIF) was used to image the intermediate species, OH and CH_2O. The fluorescence images were captured by two different intensified CCDs (ICCD) and excited by two laser beams from separate laser systems as shown in Fig. 2. The excitation laser for OH was 283.522 nm (A-X(1, 0) Q1(4)) from the 2nd harmonic of a dye laser pumped by the 2nd harmonic of Nd:YAG, and the CH_2O excitation laser was at the wavelength of 355nm from the 3rd harmonic of Nd:YAG. The output power of the two lasers was ~20 mJ/pulse for OH and ~250 mJ/pulse for CH_2O. Both laser pulses possessed a duration of about 10 ns and a repetition rate of 10 Hz. The two laser beams were formed into overlapping co-planar laser sheets. The heights of laser sheets were all ~60 mm, of which the central 46-mm portion with nearly uniform power distribution was presented here. The pulses were controlled by a pulse generator, to illuminate the flame sequentially with a separation of 200 ns in order to reduce the interference among different light signals, as shown in Fig. 3. The flow field can be regarded as frozen in the time of 200 ns.

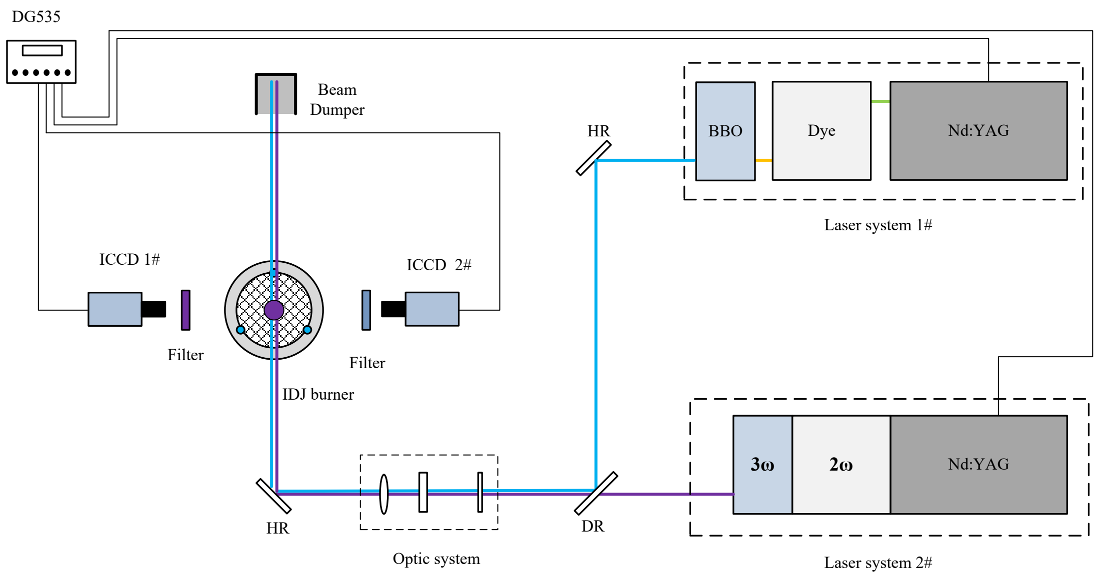


Fig.2 Schematic of the experimental setup for simultaneous multi-species PLIF imaging

Each PLIF signal was detected normal to the laser sheet with a gated ICCD. Two optical filters were implemented respectively before the two ICCDs to block the laser scattering and reflecting. A bandpass filter (Semrock, FF02-320/40-25) was used for OH-PLIF detection, and a 355nm notch filter for CH_2O-PLIF detection. Before the PLIF detection, a calibration method with high spatial revolution was developed to match the images of different species.

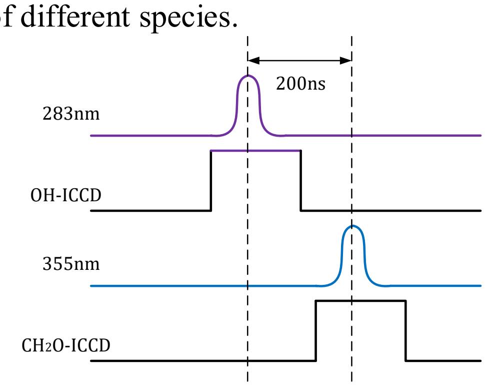


Fig.3. Synchronization scheme of OH/CH2O-PLIF

It needs to point out that the Rayleigh scattering signal for temperature measurement could be acquire using the CH_2O-ICCD and 355nm laser pulse with different filter (355nm narrow pass). If another separate camera is introduced, and a dichroic mirror is used between OH-ICCD and Rayleigh camera to separate the fluorescence and Rayleigh scattering signal, the two dimensional distribution of two radical species (OH/CH_2O) and temperature could be measured simultaneously. More detail information of interaction between flow and combustion could be recognized while the third camera is in place.

3 Results and discussion

3.1 Instantaneous images of multispecies

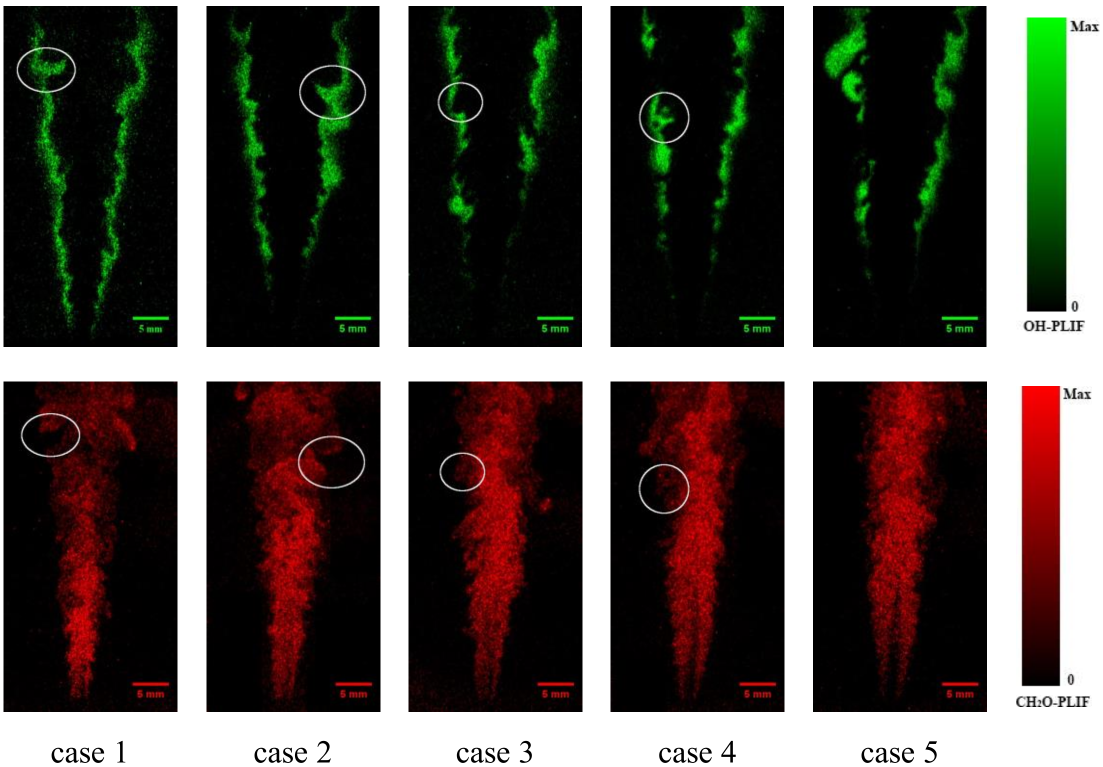
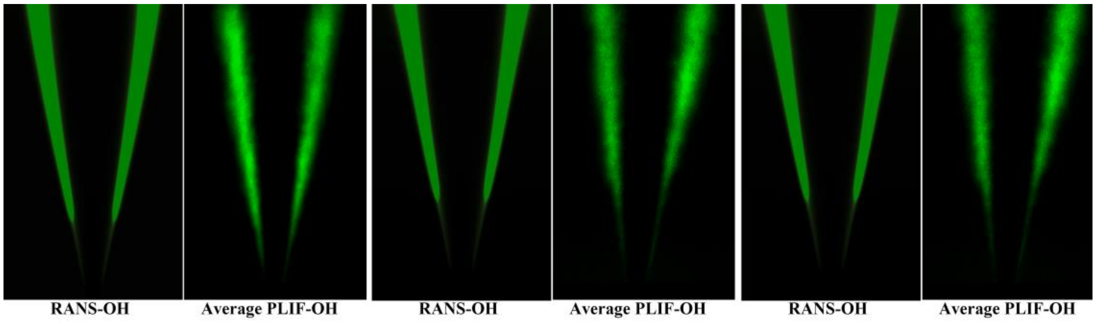


Fig. 4. Simultaneous imaging of OH and CH2O for the 5 experiment conditions

Fig. 4 shows the simultaneous measurements of OH/CH_2O PLIF for the 5 experiment conditions listed in Table 2. It can be seen from the figure that, the OH is distributed in the reaction region, and the CH_2O is located in the induction region. The edges of the OH and CH_2O fit well with each other, especially as marked with white circle in Fig. 4, which confirms the frozen field flow in the time of 200ns and the reliability of the 'simultaneity' of measurements. With the increase of the jet velocity, the OH signal becomes weaker and the CH_2O signal stronger. This is because the increase in jet velocity reduces the residence time of CH_2O and transports CH_2O to the downstream of the flame. The OH distributions become broken more and more heavily with the increase of jet velocity, which means the extinction and re-ignition of the flame. Also the flames become more and more wrinkled. When the jet velocity increases, the higher turbulences tear the flames and broke them into smaller turbulent eddy, which leads to the local extinction.

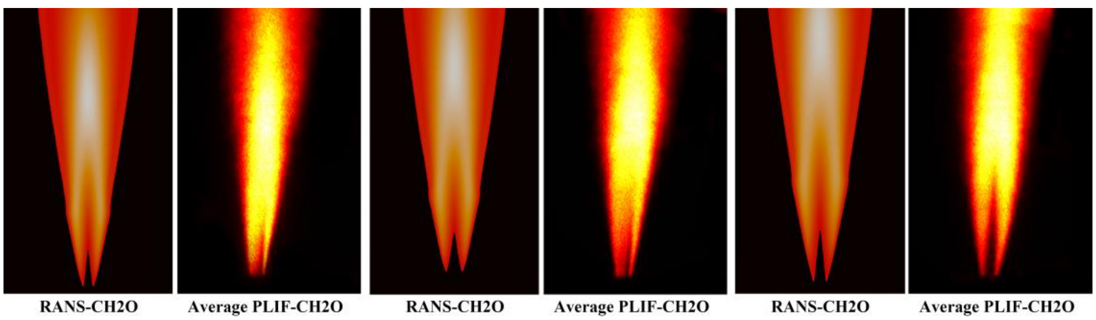
3.2 Comparison to RANS

In order to validate the accuracy of the PLIF, simulations are conducted with a C_2H_4/AIR skeletal chemical kinetic mechanism [23]. The ReactingFoam solver in OpenFOAM [24] is used to conduct simulation with k-Omega SST [25] turbulence model and PaSR [26] combustion model.



Case 2 Case 3 Case 5

Fig. 5. Comparisons of the RANS-OH and averaged OH-PLIF images



Case 2 Case 3 Case 5

Fig. 6. Comparisons of the RANS-CH2O and averaged CH2O-PLIF images

Fig.2 is the comparison of the RANS and averaged PLIF signal. From the image we can see that the numerical simulation results and the experimental results are well calibrated, and the flame structure is well simulated. With the increase of the jet velocity, the position where OH appears moves to downstream of the flame, and the position where the maximum value of CH_2O also moves to downstream.

The detail information about flame structure and flow field are indicated from the images and measurement results. It is clear that the flames have different features at the two measurement locations above the fuel-jet exit plane. These locations were chosen to represent two oxidant regimes, which can be defined as diffusion combustion and partial premixed combustion.

3.3 Analysis of accuracy

For simultaneous image of multi-species, the accuracy of measurement is depended on the calibration procession of the images from different cameras. Many factors influence the calibration precision, such as lens

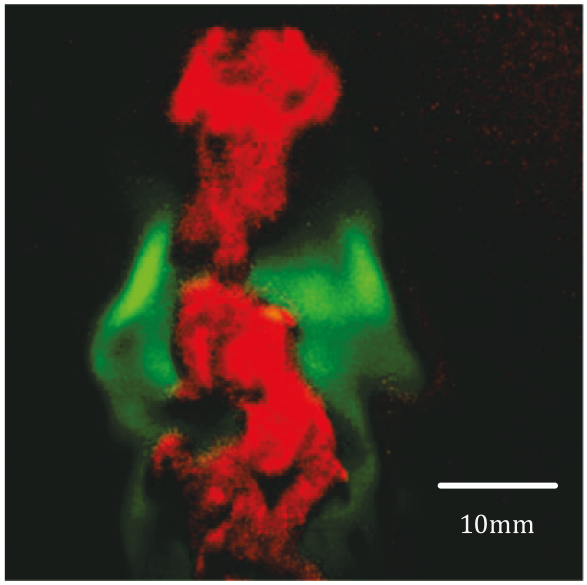
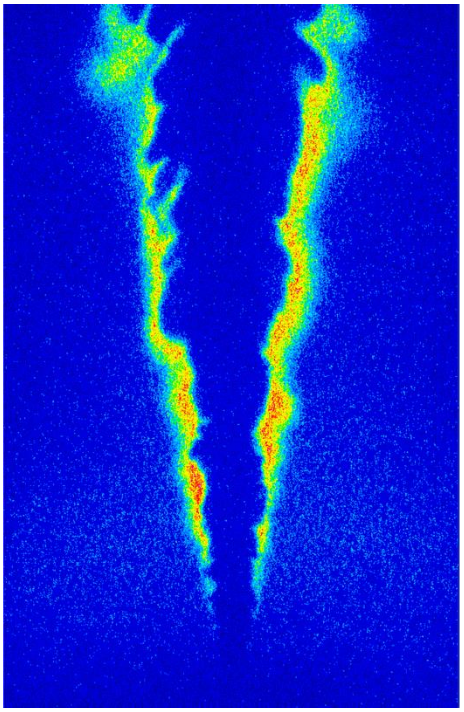
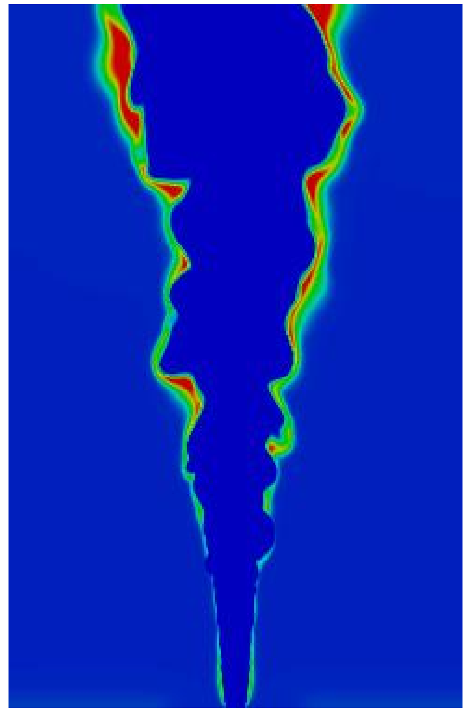


Fig.7. The local structures of OH (green) and CH2O (red)

Based on the system of multi species PLIF and Rayleigh scattering thermometer, the sonic ethylene jet flames have been studied. The data of flame structure is post-processed and analyzed from these images from ICCDs. The images from the three ICCDs are spatially matched typically to sub-pixel accuracy due to the calibration methods with high precisions. And the worst case mismatch is never more than 2 pixels (320 μm) as Fig.4.

Because of the non-uniform distribution of laser beam in pulse power and profile, the images of fluorescence are corrected by accessory fraction of monitoring laser sheet. The reliability on detecting radicals and temperature of our system is validated by using Bunsen burner and flat-flame burner. The signal to noise ratio (SNR) of the instantaneous OH fluorescence is better than for Rayleigh and CH_2O because of higher excitation efficiency. As displayed in Fig.8, the image is well according to the simulation results in general, even the position and width of the OH layer. But in the area near to the nozzle, no OH signal is captured, because of the thin reaction layer.

OH-PLIF DNS-OH

Fig.8. The comparison between OH-PLIF image and simulation results of LES

The temperature using Rayleigh scattering thermometer could be achieved through calculating the Rayleigh images, and the accuracy not only comes from the SNR of Rayleigh signal but also from Rayleigh scattering cross section, which is based on the temperature, major species and their mole fractions. Typically, the cross sections are different between lean and rich position in a flame. A reasonable assumption has been built based on the laminar non-premixed flame calculations, and the Rayleigh cross section variations are calculated.

4 Conclusion

The flame structures, flow field and concentration distributions of radicals in sonic ethylene jet flames are measured and presented to indicate the mechanism between combustion reaction and high speed turbulent flow. Simultaneous imaging measurements of the hydroxyl radical (OH), formaldehyde (CH_2O) helps to understand the interaction between turbulence and combustion. It seems the mismatch of two type images cannot be ignored, and then this error will influence the accuracy of the heat release rate calculation. Therefore, the methods and skills for multispecies PLIF and other simultaneous measurement need to be deal carefully.

Acknowledgments

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