Planar Laser Induced Fluorescence Imaging of OH Radical in Supersonic Combustor

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Abstract

Planar Laser Induced Fluorescence (PLIF) technique was utilized to measure the images of hydroxyl radicals (OH) fluorescence and spontaneous emission in hydrogen/air and kerosene/air supersonic combustion. The results showed that PLIF has been an efficient approach for identification of fuel/air mixing and combustion process. It was found that large number of OH radical is concentrated in the cavity range of the combustor, it is helpful to understand the mechanism of the cavity as the flame-holder in supersonic combustion.

Keyword: *PLIF, supersonic combustion, OH radical*

1. Introduction

Supersonic combustion is a complicated process, in which fuel and air is mixed and produces combustion chemical reaction in case of supersonic flow, strong shock waves and chemical thermal release exist in the flow field. For this kind of complicated flow field, it will be difficult to conduct experimental measurements especially physical probe could not be utilized. Non-invasive optical measurement techniques provide a powerful flow visualization method. Based on single point laser diagnostics, coherent anti-Stokes Raman spectroscopy, CARS, has been successfully applied to measure temperature and species concentrations in combustion investigations [1]. Planar laser-induced fluorescence, PLIF, imaging method has already been suggested and demonstrated to be a potential tool for combustion diagnostics [2].

Laser-induced fluorescence, LIF, denotes the radiation emitted by a molecule or atom in an "allowed" transition from a higher to lower energy state after excited by a laser source. The LIF signal is several order levels stronger than that of Raman technique, this technique can be used to measure concentrations of the OH, NO, CH, and CN radicals. It provides a powerful method for studies of combustion chemical reaction dynamics and flame structure. Earlier, the LIF technique is a single point laser diagnostics, the PLIF technique has already been demonstrated for instantaneous, i.e. single laser shot, non-invasive mapping of species concentration, temperature, velocity, and pressure [3,4].

A Cavity has been widely applied to stabilize the flame in the supersonic combustion studies, more experimental data are still needed to understand the mechanism of the cavity as the flameholder in supersonic combustor. The aim of this paper is to measure the OH radical images in the supersonic combustor by using the PLIF technique and to analyze the supersonic combustion filed. The measurements were focused in the cavity range of the combustor. The $Q_1(8)$ line of OH radical was exited since that the population is insensitive to temperature.

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2. Basic Principles of Laser-Induced Fluorescence

Laser-induced Fluorescence, LIF, is a well-established sensitive technique for detecting population densities of molecules and/or atoms in specific quantum states. Fluorescence denotes the radiation emitted by a molecule or atom when it decays by spontaneous emission of a photon in an "allowed" transition from a higher to lower energy state. In LIF measurement, molecules or atoms in the ground electronic state are exited by a laser source, and transit to an upper state, the upper state is populated, typically, the LIF signal will be resonant enhanced with an emission frequency tuned to a resonance between the exited state and a lower state. After excitation, the laser populated upper state may undergo molecular excitation and inelastic collisions with other molecules, i.e. energy transfer, producing the LIF signal.

The LIF signal, *F*, can be related to specific properties, e.g. temperature, *T*, pressure, *P*, and concentrations of the molecules or atoms, χ, [1,3]

$$F = \frac{E\chi P}{SkT}\sum f_J Bg\frac{A}{A+Q}\eta$$

where, *E* is the energy of the laser source, *S* the interaction area between the laser sheet and molecules or atoms, *k* the Boltzmann constant, f_J the Boltzmann expression with rotational quantum number *J*, *B* the Einstein coefficient, *g* the spectrum conclusive calculus, *A* the spontaneous emission rate, *Q* the quenching rate, η the fluorescence transfer efficiency of the ICCD, $A/(A+Q)$ is so-called fluorescence producing efficiency.

The particular rotational level, *J**, which is least sensitive to temperature variations, can be expressed as [1]

$$J^{*2} + J^{*} - \left(\frac{k}{hcB_v}\right)\overline{T} = 0$$

where, $\overline{T}$ is an average flame temperature and *J** the rotational number, whose population is least sensitive to temperature changes. For the OH radical, J^*=8.5 ($Q_1(8)$ line) at temperature range of 1000~2600K, and J^*=5.5 ($Q_2(6)$ line) at temperature range of 900~1700K. Therefore, by judiciously selecting the initial level for excitation, namely *J**, the measurements becomes quite insensitive to temperature.

3. Experimental Setup

3.1 Supersonic Combustion Setup

Figure 1 shows the schematic of the supersonic combustor, details of this facility were described by Yu *et al* [5], that had an entrance cross section of 50mm×70mm, and length of 1020mm. Nearby the cavity, there are tow quartz windows of 47mm in width and 80mm in length. The cavity, as the flameholder, is located at 290mm far away from the entrance of the combustor. The cavity was of 12mm in depth, 88mm in length, and 45 degree in after ramp angle. High temperature vitiated air was provided by burning hydrogen, oxygen, and air in a heater with the resulting oxygen volume fraction equal to that of the normal air. The system was controlled using a computer and capable of supplying heated air up to flow rate of 2.0kg/s, stagnation temperature of 2100K, and stagnation pressure of 4.5MPa. The airflow was then accelerated to Mach 2.5 with a two-dimensional nozzle.

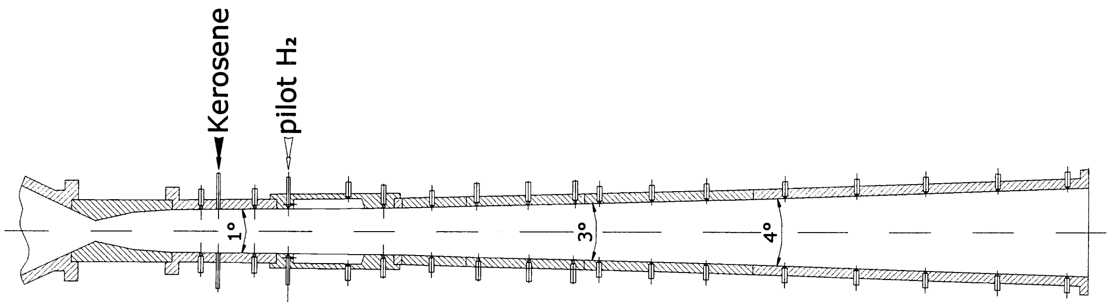


Fig. 1 Schematic of supersonic combustor

3.2 The PLIF Arrangement Setup

Planar Laser Induced Fluorescence (PLIF) imaging of OH was applied for the characterization of supersonic combustion in the cavity region. Figure 2 shows the present OH PLIF system. A Spectra Physics GCR290-30 Nd: YAG laser (30Hz) was frequency-doubled to 532 nm (800mJ/pulse), which was then used to pump a Lumonics HD-500 Dye laser. The doubled-frequency output of the dye laser was of 283.642 nm, 5mJ/pulse, 5ns pulse width, and 100MHz band width, which was used to excite the $Q_1(8)$ branch in $X^2\Pi - A^2\Sigma^+(0,1)$ band of OH radical. A cylindrical lens (f = 5mm) combined with a spherical lens (f = 400mm), convert the beam into a expanding sheet, which was approximately 120mm wide and 0.4 mm thick. The OH fluorescence signal was collected using a Princeton Instruments ICCD 1152MG-E (1024×298 pixels) camera along with a Nikon UV-Nikker f/4.5 lens (f = 105mm). Additionally, three 2mm Schott UG-11 filters were used to block the visible and infrared luminosity resulting from kerosene/air combustion, while a WG305 filter was used to block the laser scattering.

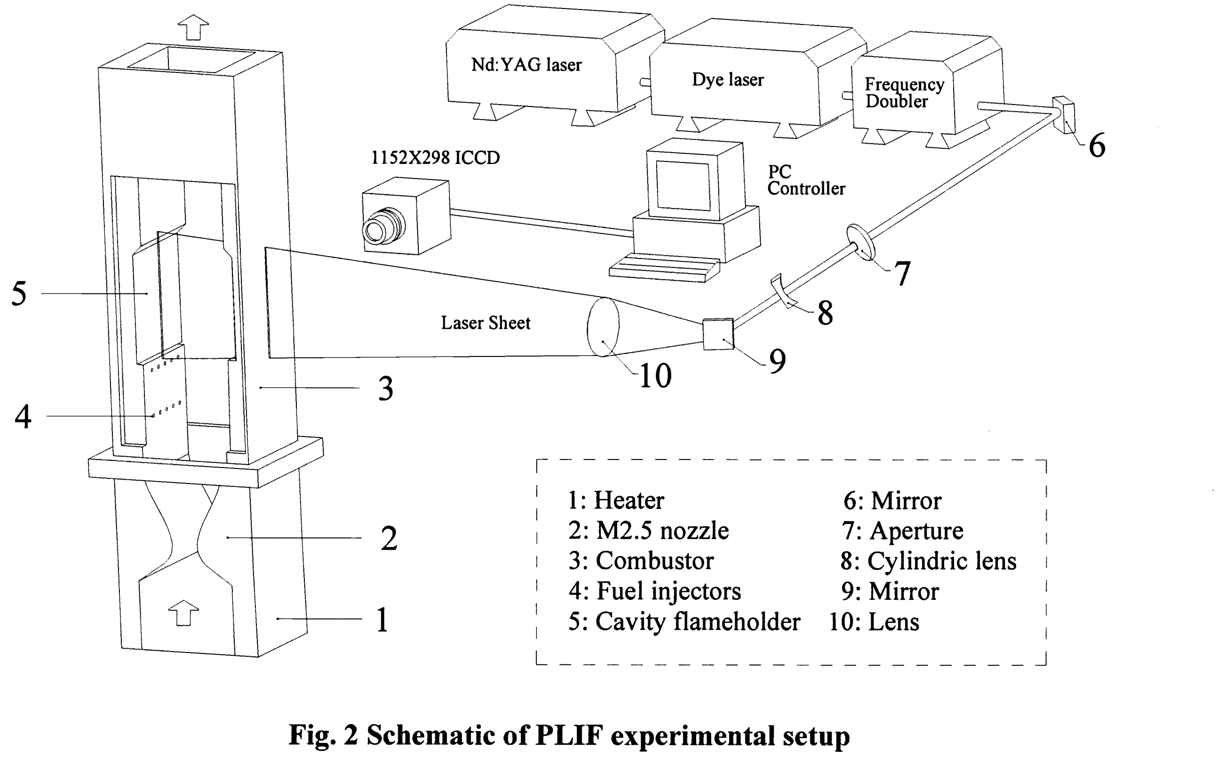
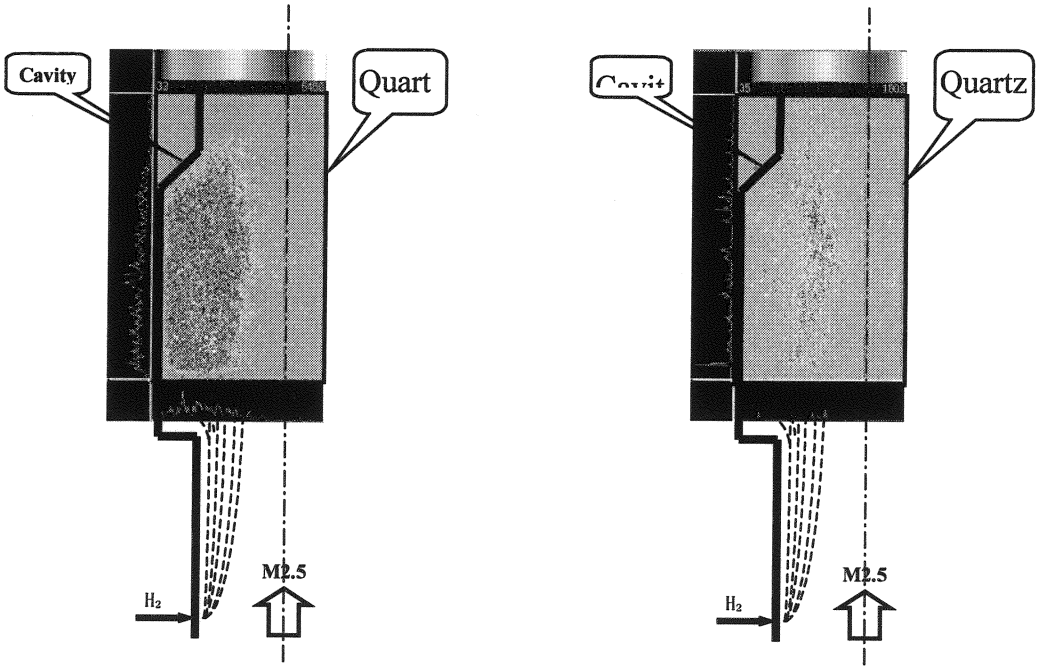


Fig. 2 Schematic of PLIF experimental setup

4. Results and discussions

4.1 Fluorescence image of OH radical in hydrogen/air supersonic combustion

Figure 3A shows the laser induced fluorescence image of OH radical measured in hydrogen/air supersonic combustion taken in case of stagnation temperature of 1750K, stagnation pressure of 10.6Mpa, and 0.45 in the equivalence ratio of hydrogen/air. For symmetries of combustor structure and injection of fuel hydrogen, the measurements were focused on one side of the combustor nearby the cavity range. Exposure of imaging is one second (30 laser pulses). From the measured image, firstly, the combustor is not full of the OH radicals, the OH radicals mainly distribute in the sidewall region, and there is less OH radical in the center of the combustor. It indicates that the combustion did not reach the middle region, and the fuel mixture is not perfect. In addition, the OH radicals distributed in the sidewall region and were non-uniform, the OH radicals are mainly concentrated in the cavity and nearby the cavity region. Due to the existence of low-speed region in cavity, the OH radicals produced in the chemical reaction in the cavity region were maintained, and formed steady combustion. Combustion occurred nearby the right of OH radical range. Because of the influence of high speed airflow, the horizontal injection depth of hydrogen is limited, and it is difficult to form steady burning flame in the central region. To identify that the measured image is the fluorescence image of OH radical, the spontaneous emission during the combustion has also been measured. As shown in figure 3B, the strength of the spontaneous emission is much weaker than that of fluorescence emission of the OH radical. It indicates that the spontaneous emission has much weaker influence on the OH radical fluorescence measurements in the hydrogen/air supersonic combustion.

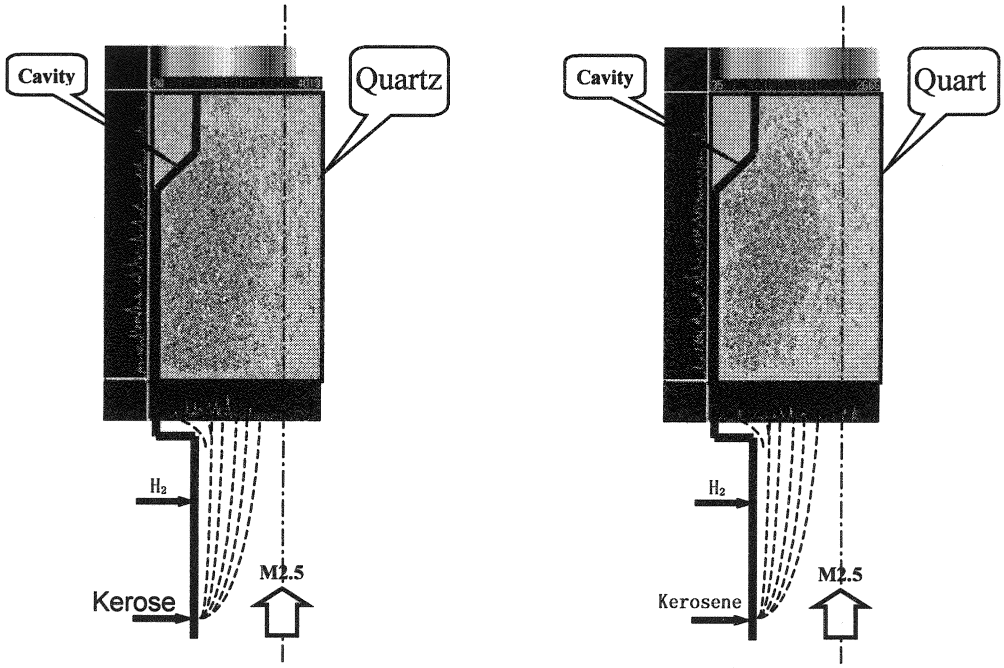


A. OH radical PLIF image

Fig. 3 PLIF image in H_2/air supersonic combustion

4.2 Fluorescence image of OH radical in kerosene/air supersonic combustion

The laser induced fluorescence image of OH radical measured in kerosene/air supersonic combustion is shown in figure 4A taken in case of stagnation temperature of 1750K, stagnation pressure of 10.5Mpa, and 0.34 in the equivalence ratio of kerosene/air. The obtained image is similar to that in the hydrogen/air supersonic combustion (figure 3A). The OH radical distributed in sidewall region of the combustor, and is non-uniform. The OH radical is concentrated in the cavity and nearby the cavity region. It indicates that the steady combustion region is nearby the cavity. However, the spontaneous emission image taken in the kerosene/air supersonic combustion is different from that in the hydrogen/air supersonic combustion (figure 3B). As shown in figure 4B, the strength of the spontaneous emission is much stronger than that in the hydrogen/air supersonic combustion. It indicates that there was much stronger interference of background emission in the fluorescence image shown in figure 4A, including ultraviolet spontaneous emission of OH radical, the visible emission of the flame (near infrared emission), Rayleigh scattering from the incidence laser in combustor, and ultraviolet spontaneous emission of carbon particle (such as C_2, C_3 etc). It is because that the chemical reaction process in the carbon-hydrogen fuel (kerosene) combustion is much more complicated than that in the hydrogen combustion, and the intermediate products are complicated too. There are spontaneous and exited emission spectral lines and bands in the ultraviolet spectral region produced by these intermediate products (such as C_2, C_3, CN and CH, etc). Although the optic filter UG11 was used to isolate visible and the WG305 to isolate Rayleigh scattering of ultraviolet incidence laser in LIF measurements, the efficiency of the optic filter could hardly be 100%, and also the ultraviolet emission produced by C_2, C_3, CN and CH radicals could not be isolated. The great difficulties were brought to the analysis on OH radical fluorescence. As it is difficult to distinguish the fluorescence of the OH radical from the emission fluorescence images taken by the ICCD. It is also a problem in the laser-induced fluorescence measurements of the carbon-hydrogen fuel combustion. Therefore, the spectral analysis technique should be introduced, that is, through the analysis of the fluorescence spectrum, the key molecules contributed to the fluorescence can be determined. This will be our future works.



A. OH radical PLIF image

Fig. 4 PLIF image in kerosene/air supersonic combustion

From the above-mentioned analysis, the PLIF image in kerosene/air supersonic combustion was very complicated, and the image could not be described as a "pure" OH radical fluorescence image, but the measured fluorescence image directly mapped the kerosene/air supersonic combustion. The existence of fluorescence mapped the chemical reaction region in the combustor as the fluorescence was emitted using those intermediate products produced in the chemical reaction process.

5. Conclusions

Planar laser induced fluorescence technique is a powerful approach to diagnose supersonic combustion. The fuel/air mixing process can be identified by the distributions of the OH radical. The PLIF images of the OH radicals obtained in the supersonic combustion show that the OH radicals are concentrated in the cavity and the sidewall region of the cavity, it is helpful to understand the mechanism of the cavity as the flame-holder in supersonic combustion, and it was found that the spontaneous emission in the hydrogen/air supersonic combustion was much weaker, while the spontaneous emission in the kerosene/air supersonic combustion is much stronger and more complicated.

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