

Calibration method for 2D instantaneous OH-PLIF temperature measurements in flame

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Noninvasive technology for measuring instantaneously two-dimensional (2D) temperature distributions of flame using two-color planar laser induced fluorescence (PLIF) of OH is investigated. A calibration method is researched and developed. This method is based on the calibration experiments with a laminar premixed flame and thermocouple, and avoids complex calculation and uncertainty of the spectrum parameters. Measurements for a flat burner at ambient temperature under atmospheric pressure are also presented; calibration results are used to diagnose a supersonic combustion in scramjet combustor. The conclusion indicates that this method is useful, and a better precision of calibration can be acquired by correcting the line shapes of the spectral lines and lasers.

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Planar laser induced fluorescence (PLIF) is an attractive flow-measurement technique in combustion and high-speed aerodynamics research. This laser-based diagnostics is advantageous in some special and severe environments and flow fields, because they are nonintrusive and robust. PLIF can measure two-dimensional (2D) concentrations of molecules, such as OH, CH, NO, and CO^[1-5]. Moreover, the two-color PLIF methods offer the advantage of 2D temperature measurements that yield information about special structure and temperature distributions with high temporal and spatial resolution^[6-8]. OH is an important reactive intermediate in combustion. Thus, using OH radicals as indicator is a perfect choice because of its abundant concentration at high temperature and its spectroscopic characters.

Several thermometry methods based on laser and spectra technique have been developed. Especially, Seitzman *et al.* have developed temperature measurements with OH-PLIF^[6,7]. In their representative work, the temperature distribution of flame has been acquired by laser-induced fluorescence (LIF) imaging and calculation with the data of the two spectrum lines selected^[8]. In the recent years, several PLIF-thermometry works similar to the results in Refs. [6-8] have been performed in various combustion experiments^[9-12]. However, the spectrum data used are difficult to confirm and correct in complex combustion environment, thereby influencing the accuracy of the OH-PLIF measurement. Therefore, an effective calibration method is needed.

In this letter, a double-pulse PLIF experiment system is set up to study the two-color OH-PLIF thermometry technique. A calibration method for this technique has been developed using the flat flame burner and thermocouple. Furthermore, the calibration experimental results are used to correct the transient temperature distribution of a turbulent flame.

According to the OH-PLIF principle^[13], the total fluorescence signal intensity I_f for the line, obtained from exciting with a laser intensity I_l from level i in the ground

state to level i^* in the excited state, is given by

$$I_f = \alpha \cdot N_i \cdot B_{ii^*} \cdot I_l \cdot g \cdot \eta, \quad (1)$$

where α is an instrumental constant comprising light collection efficiency, filter and detector quantum efficiencies, electronic gain, etc.; B_{ii^*} is the absorption coefficient; N_i is the population in the level i ; g is the overlap integral of the absorption line shapes g_{abs} and laser line shapes g_{laser} , and given by

$$g(\nu_l, \nu_a) = \int_{-\infty}^{+\infty} g_{\text{abs}}(\nu, \nu_l) g_{\text{laser}}(\nu, \nu_a) d\nu, \quad (2)$$

where ν is the frequency, and ν_l and ν_a are the center frequencies of the lines above. The quantum yield η is known as $A/(A+Q)$, and A is the effective rate of spontaneous emission for all directly and indirectly populated states. Similarly, Q is the total electronic quenching rate of the excited states. For the two-color PLIF thermometry technique, a ratio of signals is taken, exciting first one transition, and then another from the same lower vibrational level but a different rotational state. The signals are formed by the summation of the two LIF signals captured at the same time, which are given by

$$I_f^{(1)} = \alpha^{(1)} \cdot N_i^{(1)} \cdot B_{i1}^{(1)} \cdot I_l^{(1)} \cdot g^{(1)} \cdot \eta^{(1)}, \quad (3)$$

$$I_f^{(2)} = \alpha^{(2)} \cdot N_j^{(2)} \cdot B_{j2}^{(2)} \cdot I_l^{(2)} \cdot g^{(2)} \cdot \eta^{(2)}, \quad (4)$$

where one is the excited state 1 after excitation from the ground state level i , and the other is the state 2 excited from level j . The ratio of the ground state populations N_i and N_j according to Boltzmann statistics is given by

$$\frac{N_i}{N_j} = \frac{2J_i + 1}{2J_j + 1} \cdot e^{-\frac{(E_i - E_j)}{kT}}, \quad (5)$$

where $(2J+1)$ and E are the degeneracy and energy of a ground state with rotational quantum number J , respectively, and T is the temperature. Combining these three equations yields the desired relationship between the temperature and the ratio of the fluorescence signals

following excitation from two different rotational levels of the electronic ground state:

$$e^{-\frac{(E_i - E_j)}{kT}} = \frac{I_f^{(1)}}{I_f^{(2)}} \cdot \frac{I_1^{(2)}}{I_1^{(1)}} \cdot \frac{\alpha^{(2)}}{\alpha^{(1)}} \cdot \frac{B_{j_2}^{(2)}}{B_{i_1}^{(1)}} \cdot \frac{g^{(2)}}{g^{(1)}} \cdot \frac{\eta^{(2)}}{\eta^{(1)}} \cdot \frac{2J_j + 1}{2J_i + 1}. \quad (6)$$

The temperature of a flame can be measured by detecting the ratio $R = \frac{I_f^{(1)}}{I_f^{(2)}} \cdot \frac{I_1^{(2)}}{I_1^{(1)}}$ experimentally, and the relation of T and R is established as

$$R = C_{12} \frac{g_1}{g_2} \frac{2J_1'' + 1}{2J_2'' + 1} \frac{S_{J_1'' J_1'}}{S_{J_2'' J_2'}} \times \exp\left[-\frac{F(J_1'' - J_2'')}{kT}\right] \frac{A + Q_2}{A + Q_1}, \quad (7)$$

where $S_{J'' J'}$ is the normalized Honl-London factor of the LIF line used and $F(J'')$ is the rotational term energy of its lower level; C_{12} is a normalization constant that is correlative with the experiment system and the properties of the two LIF lines selected. Choosing one line that is insensitive to temperature and another with an intensity varying greatly with temperature, the fluorescence intensity ratio of these two lines can be calculated with the theoretical data generated by the simulation program LIFBASE^[14] to correct temperature. In this study, the P1(1.5) and Q1(5.5) transition lines in the $A^2\Sigma^+ \leftarrow X^2\Pi(1,0)$ band at 282.25 and 282.74 nm are selected. The temperatures corresponding to the ratio R of these two lines are shown in Fig. 1, with $C_{12} = 1$. The value of C_{12} depends on the optic layout, efficiency and responsibility of the intensified charge-coupled device (ICCD) image system and laser parameters, and varies for deferent experiment. Apparently, confirming the value of C_{12} is complex and difficult.

According to the LIF-thermometry principle, a double-pulse OH-PLIF experimental setup is shown in Fig. 2.

An instantaneous temperature measurement requires two laser pulses with wavelengths according to two special absorption lines of the OH radical, and with a temporal delay shorter than the time scale for the fastest process that can freeze the structure of the flame. Tunable UV laser pulses (282.25 and 282.74 nm) are generated by two laser systems (Continuum PR2 8010, named 1# and 2#, respectively), which consisted of the frequency-doubled Nd:YAG lasers (532 nm), dye laser pumped by 532-nm laser, and UVT (creating UV laser near 282 nm by frequency doubling of the dye laser). The two UV

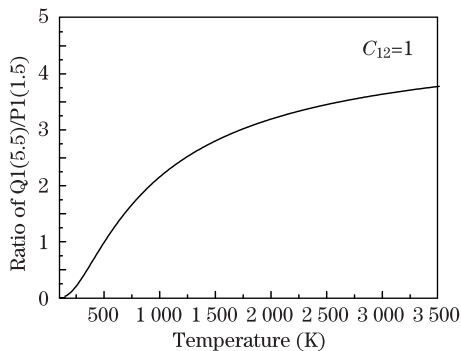


Fig. 1. Temperature as a function of the intensity ratio R obtained by LIFBASE.

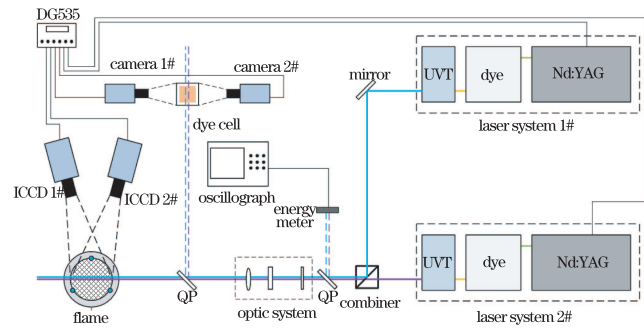


Fig. 2. Double-pulse PLIF experimental arrangement.

laser pulses became planar laser sheet (thickness of 0.5 mm, width of 100 mm) and through the flame by optic combiner and lens system. Both UV laser pulses have a duration of less than 10 ns. Typical pulse energy is about 10 mJ per pulse, at a bandwidth of 0.5 cm^{-1} .

The fluorescence signals of the OH are detected by two intensified-CCD camera systems (Andor DH734, 1024×1024 pixels) using UV lenses and interference filters (WG305 and UG11), which are used to clean up laser scattering and reflecting. The two cameras are placed on the same side of the flame and laser sheet at a right angle. The intensity distribution of the laser sheets is monitored using quartz cells filled with Rhodamine 590 dye solution and equipped with two additional charge-coupled device (CCD) camera systems. Furthermore the energies of the laser pulses are detected by an energy meter and monitored by an oscilloscope (Tektronix DPO7104). Thus, each set of cameras records the fluorescence signal from the excitation of the two rotational levels and the laser intensity distributions; the oscilloscope records the energy of the two laser pulses.

Generating an appropriate trigger for the laser systems and cameras is necessary to measure the simultaneous temperature distribution. The signal processing arrangement consists of one control computer and two pulse delay generators (SRS, DG535). When the first laser sheet pulse reached the flame position, the intensifier of the ICCD 1# is activated to capture the fluorescence induced. The second intensifier is active when other laser pulse reached with a relative time delay of 200 ns. Each laser sheet pulse thus arrived at the test section at the same time relative to its respective intensifier gate.

The intensifier for the camera mounted above the test section is activated just before the laser to capture the part of the fluorescence burst due to the prompt laser sheet, whereas the same fraction of the fluorescence induced by the delayed sheet, beginning 200 ns later, is captured on the camera mounted below the test section, in addition to the portion of the fluorescence induced by the first sheet that occurred when the second intensifier is active. Figure 3 shows the time scheduling of the intensifier gates, input laser pulses, and fluorescence decays. The laser systems are operated at 10 Hz, with the ICCD at 1 Hz. The fluorescence lifetime of OH is longer than 200 ns, thus the fluorescence induced by the first laser pulse overlaps with the camera gate. However, the signal is very weak and the majority of the luminescence intensity of the fluorescence is captured by the corresponding ICCD. This uncertainty induced by the overlaps in time scheduling can be ignored.

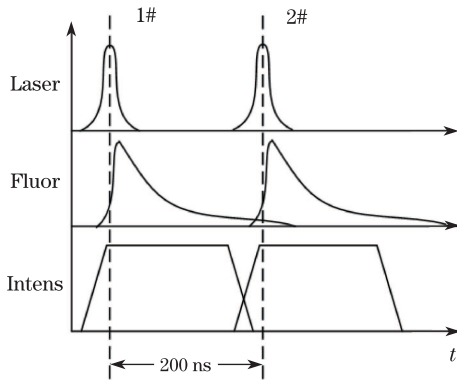


Fig. 3. System scheduling.

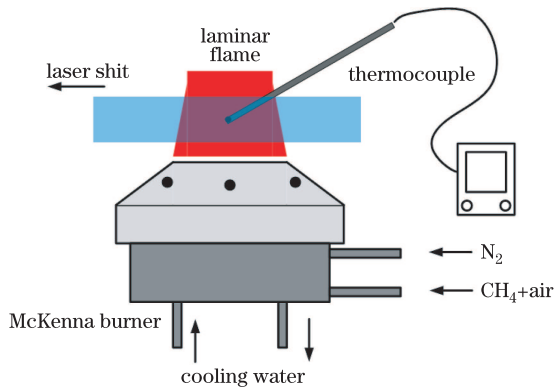


Fig. 4. Calibration experimental arrangement.

The ratio of two LIF lines R is calculated from the PLIF images and laser parameters measured by the system above. Care must be considered in both the acquisition and analysis of the data to obtain accurate temperature, another precision of the constant C_{12} . In a previous study, C_{12} allows the measured ratio to be scaled to an expected zone in the flow field where T is known. Thus, the value of C_{12} can be confirmed by the calibration experiment based on a normal flame.

The McKenna flat flame burner is the perfect burner to produce steady laminar flame flow^[15]. This burner is constructed with a steel housing, sintered bronze burner plug and shroud ring, and a copper cooling coil. For the calibration experiment, the McKenna burner was placed in the measurement zone in the PLIF experiment system (see Fig. 1), and steady laminar air-CH₄ flame was PLIF diagnosed. A bare wire thermocouple was then used to measure the temperature of few points at the section lighted by the UV laser. The thermocouple leads were isolated using a two-hole alumina ceramic insulator, and held in place by a clamp attached to a high precision 3-axes stage.

The PLIF system for the calibration experiment is completely the same as the one used in combustion diagnosis. First, the thermocouple stand is set up next to the flat flame burner, as shown in Fig. 4. In addition, the bread is positioned to a desired zone, where the temperature is measured. The position of the bread is recorded by the ICCD camera without optical filter. After shifting away the thermocouple, the laser and data acquisition system (including camera, ICCD, and energy

meter) is ready to take experimental images. Finally, two series of OH fluorescence images of the steady flame are acquired by two ICCD cameras when the two UV laser pulses influence the flame.

The average OH fluorescence images are calculated by the two series pictures and the corresponding energy parameters. Furthermore, the average images are adjusted and compensated by the recorded shape of the laser sheet after image calibration processing. Figure 5 indicates the average OH fluorescence images after calculation; Fig. 5(a) is the P₁(1.5) image and (b) is that of Q₁(5.5).

The ratio R on every image pixel cell is acquired based on the function, $R = \frac{I_f^{(1)}}{I_f^{(2)}} \cdot \frac{I_f^{(2)}}{I_f^{(1)}}$. The relationship between ratio R and temperature value measured by the thermocouple is established to calibrate other special and complex flame and combustion. The normalization constant of this OH-PLIF system is then confirmed. Figure 6 is the 2D temperature distribution of the laminar air-CH₄ flame on the McKenna flat burner.

Other complex flame can be quantitatively measured by two-color PLIF using this calibration results. A supersonic combustion in scramjet combustor is studied using the OH-PLIF system and the two-color temperature measurement method. The combustor model consists of a rectangular duct, incorporating a cavity. The fuel is H₂ gas. Optical access for the PLIF images is obtained using UV fused silica windows in the top and side walls of the combustor. The top window allows access for the laser sheet, whereas the side window allows transmission of the fluorescence signal to the camera. The windows allow a region from the upstream of the cavity leading edge to the downstream of the leading edge.

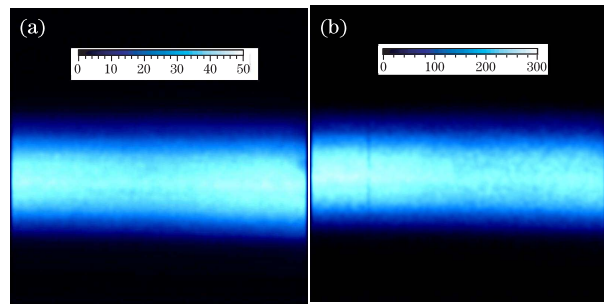
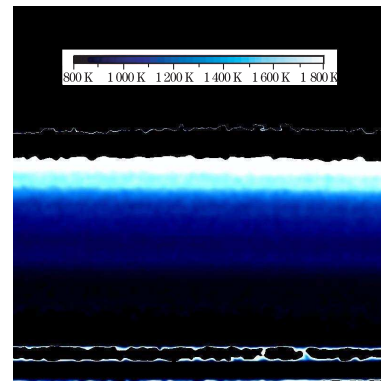
Fig. 5. Average OH fluorescence images of (a) P₁(1.5) and (b) Q₁(5.5).

Fig. 6. 2D temperature field distribution.

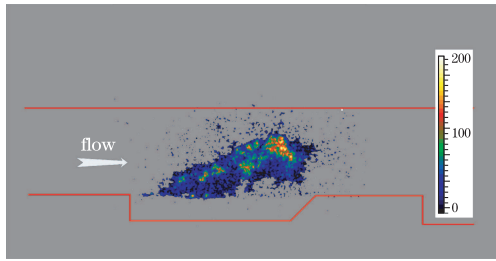
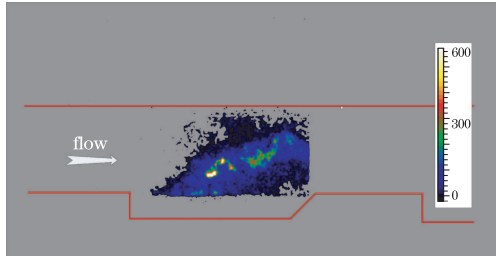
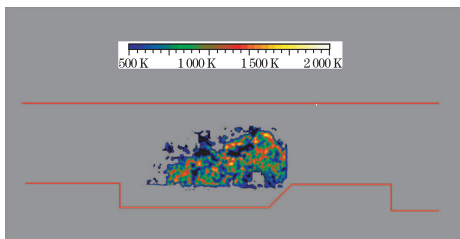
Fig. 7. OH fluorescence for $P_1(1.5)$.Fig. 8. OH fluorescence for $Q_1(5.5)$.

Fig. 9. 2D temperature field distribution.

Figures 7 and 8 are the fluorescence images, which indicate the OH fluorescence captured by two different ICCD cameras with $P_1(1.5)$ (Fig. 7) and $Q_1(5.5)$ (Fig. 8) lines induced. Then the 2D temperature distribution of the flame is acquired by calculating the OH fluorescence image and the calibration results shown in Fig. 9, indicating that the temperature on the special zones where the OH density is higher are quantitatively detected.

According to this calibration method, the equipments, such as laser, time control, and image capture systems, are completely same as those used in supersonic combustion experiments, which lower the error induced by the instruments. The uncertainty of the thermocouple is about 1 K for the steady flame. On the other side, a low error of the 2D PLIF temperature measurement used in the calibration experiment has been reached, with the average of several OH-PLIF images and the recording of laser pulse parameters. The OH-PLIF measurement error on a high signal level for calibration can be less than 5%^[6].

However, the uncertainty of instantaneous OH-PLIF temperature measurement using this calibration method primarily lies on the error of the image spatial calibration precessing level of fluorescence intensity, and

environment parameters, such as pressure in the combustor. The steady air- CH_4 flame in the atmosphere for calibrating the variations of spectroscopy line-shape and quenching yield cause the systematic error in the measurement. The uncertainty in supersonic flow is estimated to be less than 10%.

In conclusion, simultaneous OH-PLIF and two-color temperature measurements are studied, and a calibration method based on the recognized premix flame is performed using PLIF technique. The method offers a simple solution to quantitate temperature by comparing the ratio R with the thermocouple-results, avoiding complex calculation and uncertainty of the parameters in functions. The calibration experimental results are used to measure the temperature of the turbulent flame. Consequently, this method is proven to be useful to the combustion laser diagnosis. This method would work well in low-pressure, high-speed flows such as supersonic combustion. However, in an environment with high pressure, the calibration results are not appropriate. Consequently, a more accuracy calibration method with theoretic calculation and a special burner with high pressure environment should be required.

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