Temperature measurements in a Bunsen flame by planar laser-induced fluorescence

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Abstract. The article presents the results of measuring the temperature distribution parameters based on planar laser-induced fluorescence (PLIF) of the hydroxyl radical (OH) upon excitation of the transition (1–0) of the A^2Σ^+ – X^2Π system. Thermometry is based on registration of the ratio of the radiation intensity of the transition (2–0) and transitions (0–0), (1–1). For the most frequent excitation lines Q(7), Q(8), R(14), P(2), numerical simulation of fluorescence spectra was performed using the LASKIN software. In this work, the measurement procedure for the laminar pre-mixed Bunsen flame of a methane-air mixture was experimentally worked out. It was shown that the maximum sensitivity of the signal to temperature changes is achieved when the Q(8) transition is excited. It was found that quenching of fluorescence has a negligible effect on the accuracy of temperature measurement.

1. Introduction
Non-contact temperature measurements in combustion streams are important for optimization of the burner devices and combustion chambers, increasing the efficiency of fuel combustion, and reducing the level of pollutant formation. Measurement of the temperature field allows analyzing irregularity of the spatial distribution and, in particular, identification of the areas where peak temperatures are reached.

Currently, various methods are used for optical measurements of gas temperature based on different physical principles. The most common are based on registration of the local intensity of coherent anti-Stokes light scattering (CARS), spontaneous Raman scattering (SCR), Rayleigh scattering (PP), and laser-induced fluorescence (LIF). Due to the relatively high signal intensity (compared with the other methods listed), the LIF method is most often used to register the temperature field.

In gas flows without combustion, temperature distributions can be measured (up to 1000 K) based on registration of the LIF intensity of toluene or acetone in two different spectral regions [1]. Parts of the spectrum are selected so that they do not include the laser wavelength and have the opposite sensitivity of the fluorescence intensity to temperature. NO gas is also used as a passive impurity, which allows measurements in flows without combustion and with combustion at high temperatures (2300 K) with an error of less than 10% [2]. In particular, in [2], the temperature was estimated based on a scan of the fluorescence excitation spectra with a change in the wavelength of the excitation source.

A simpler approach is to compare the local fluorescence intensity upon excitation of only two different transitions. In theory, when transitions to the same upper state are excited, it is possible to almost completely exclude the influence of such uncertain factors as quenching of fluorescence, dissociation, and ionization. However, in this case, it is necessary to excite close lower states, the
population ratio of which varies only slightly with temperature. Therefore, in practice, excitation occurs in various upper states. Moreover, the choice of transitions is not trivial, and for different conditions, different pairs of transitions demonstrate different efficiencies. Such an analysis with the aim of selecting transitions upon excitation of the hydroxyl radical OH formed during combustion was performed in [3, 4].

Further simplification in the direction of reducing the number of radiation sources can be realized by exciting a transition that is slightly temperature sensitive, which, using a calibration burner, allows one to estimate the local absolute concentration of OH. In this case, the equilibrium concentration in the combustion products allows us to estimate the gas temperature [5]. However, under these conditions, the calibration should provide identical conditions for the pressure and composition of the combustion products in order to avoid errors due to quenching of fluorescence, which is often very difficult.

Another alternative is to excite one transition and compare the fluorescence intensity in the short and long wavelength parts of the spectrum. For a certain temperature range, depending on the excited transition, this ratio increases monotonically due to an increase in the population of the upper states as a result of collision processes.

This study complements [6] and focuses on testing the method of thermometry based on the PLIF of the OH radical upon excitation of the A^2Σ^+ – X^2Π (1–0) band and registration of the ratio of fluorescence intensity between the (2–0) band and the (0–0), (1–1) bands. For computer simulation of OH fluorescence thermometry, the commercial LASKIN software package was used [7]. The method was applied for a Bunsen laminar pre-mixed flame for a mixture of methane and air [8].

2. Experimental setup

The experimental stand (Figure 1) consisted of a burner device with a profiled nozzle having an internal diameter d = 15 mm with the possibility of supplying a pre-mixed mixture of fuel and air. The total excess fuel ratio for the methane-air mixture was Φ = 0.92. Air and fuel flows were controlled by mass flow meters (Bronkhorst High-Tech) and were 10.84 l/min for air and 1.03 l/min for fuel (Re = 1000).

The system for measuring the intensity of PLIF signal of the radical OH consisted of a tunable pulsed dye laser (Sirah Precision Scan), a pulsed Nd:YAG pump laser (QuantaRay), and two cameras with image brightness amplifiers based on a UV-sensitive intensifier. The laser beam was converted into a laser sheet using collimating optics (LaVision). The formation of a laser sheet is carried out by converting a laser beam into a diverging plane of laser radiation in space using a system of cylindrical and spherical lenses; the thickness of this area is 0.8 mm, the height is 50 mm. The tunable laser excited OH fluorescence at the transition wavelength Q1(8) of the band A^2Σ^+ – X^2Π (1-0). The average energy of a pulse with a wavelength of 283 nm was approximately 12 mJ. To account for the inhomogeneity of the laser energy density distribution in the laser sheet and the change in the pulse energy from burst to burst of the laser, part of the laser beam energy (approximately 5%) was reflected by a quartz glass plate into a quartz cuvette containing a solution of rhodamine 6G. The linear mode of fluorescence was verified by changing the energy of laser radiation.

The spatial distribution of the fluorescence signal inside the cuvette was recorded using a digital camera (ImperX Bobcat IGV-B4820, 16 Mpix, 12 bit). The intensity of the OH fluorescence signal for the band (2-0) and for the bands (0-0), (1-1) was recorded by two digital cameras with image brightness amplifiers. In the second case, the Princeton Instruments PIMAX-4 camera was used (S20 photocathode, 1 megapixel, 16 bit), equipped with a UV lens and a band-pass optical filter (310 ± 10 nm). The image for the transition (2-0) was obtained using a CCD-CMOS camera (LaVision, 5 Mpix, 16 bit) equipped with an amplifier based on UV EOP (LaVision IRO, S20 photocathode). The EOP was also equipped with a UV lens and a band-pass filter (265 ± 5 nm). The frame exposure time for each PLIF image was 200 ns.
3. Results

Using the commercial software package LASKIN, numerical modeling and verification of the effectiveness of thermometry based on registration of the fluorescence of the OH radical were performed. For the main case, the gas composition corresponded to the following molar fractions of $N_2$, $CO_2$, $H_2O$ and $OH$: 72%, 9%, 18% and 1%, respectively, which simulates the composition of combustion products of the flame of stoichiometric methane-air mixture ($\Phi = 1$). Fluorescence of $OH$ was modeled upon excitation transitions $Q_2(7)$, $Q_1(8)$, $R_1(14)$, $P_1(2)$ at band (1-0) of the $A^2\Sigma^+ - X^2\Pi$ system. Figure 2 shows the time-integrated simulated fluorescence spectrum for the $Q_1(8)$ transition excitation case, which was used in experiments for temperatures of 1600 and 2000 K. The energy density of the laser pulse (whose duration was 7 ns) per unit area was set to be $5 \times 10^2$ J/cm$^2$.

![Figure 1. Scheme of the experimental setup.](image)

Figure 1. Scheme of the experimental setup.

During the simulation, the dependence of the fluorescence intensity for the transitions (2-0) and (0-0), (1-1) on the gas temperature was analyzed. It was found that the intensity of the transition fluorescence (2-0) increases almost throughout the considered temperature range (1200-2200 K) due to an increase in the population of the upper states as a result of collisions of molecules. It is shown that the ratio of the intensity of these bands increases for the entire temperature range. Figure 3 (A and B) show integrated OH fluorescence intensity for (2-0) band and (0-0) + (1-1) bands for a full range of

![Figure 2. Time-integrated luminescence spectra of OH (in the case of excitation of the Q1(8) band transition (1– 0)) for different temperatures (A – T = 2000 K, B – T = 1600 K).](image)
bands (2-0 – $I_1$, 1-1 + 0-0 – $I_2$) of spectra intensity for different temperatures. Figure 3 (C) shows the ratio of the total fluorescence intensity for the spectral ranges of 260-270 nm ($I_1$) and 300-320 nm ($I_2$), which were used in experiments. Figures 3 (C) and (D) show that the difference in different cases of integration of the spectrum intensity is insignificant for all the described transitions. The correct choice of filters (wavelength ranges) is evidenced by the fact that the difference between the ratio of $I_1/I_2$ intensities for these parts of the spectrum (260-270 nm and 300-320 nm) and the ratio of the fluorescence signals of the studied bands (2-0) and the pair (0-0), (1-1) did not exceed 5%. Figure 3 (C) shows that the $Q_1(8)$ transition has the highest temperature sensitivity among the tested transitions (i.e. above 1:5 in the range of 1200-2200 K) (the maximum value of the temperature derivative is reached for it). Therefore, this transition was considered in detail in the experiment.

![Figure 3](image-url)

**Figure 3.** A and B – integrated OH fluorescence intensity for (2-0) band and (0-0) + (1-1) bands for different temperatures, respectively. C and D – ratio between integrated OH fluorescence intensity the spectral regions of 260-270 nm ($I_1$) and 300-320 nm ($I_2$) and integrated for a full range of bands (2-0 – $I_1$, 1-1 + 0-0 – $I_2$) of spectra intensity for different temperatures, respectively.
Figure 4. A – instantaneous distributions of the image fluorescence signal intensity for (2-0) band (IRO camera) with a spatial averaging of 5 by 5 pixels, and B – for (1-1) and (0-0) bands (Pi-Max camera). C – the average temperature field obtained by taking into account the temperature calibration. The fluorescence signal is normalized to the maximum value.

Figure 5. Instantaneous fluorescence signal obtained using the two-line PLIF method (Pi-Max camera, registration at 300-320 nm). A – the fluorescence signal of the Q₁(5) transition, B – the fluorescence signal of the Q₁(14) transition. C – resulting temperature field obtained after processing these images. The fluorescence signal is normalized to the maximum value.

Figure 4 (A and B) shows the intensity distributions I₁ and I₂ of the PLIF signal for the case of a laminar pre-mixed Bunsen flame with an excess fuel coefficient Φ = 0.92. In this example, the PLIF signal was smoothed using spatial averaging. Calibration of the temperature dependence of the ratio of the fluorescence signals (captured by two different cameras with different sensitivity and gain) was performed using a type b thermocouple. Figure 4 (C) also shows the average temperature field measured using the method presented in this article based on instantaneous images obtained from two cameras and data obtained using a thermocouple. As expected, the maximum values of this ratio are reached in the combustion products behind the flame front. Figure 5 shows the OH fluorescence signal performed using the two-line PLIF method. Using a dye laser, two different transitions Q₁(5) (282.67 nm) and Q₁(14) (286.37 nm) were excited and a signal was recorded using a camera in the range of 300-320 nm. Due to the obtained temperature field by the two-line PLIF method, it can be concluded that the data obtained by the method described in this article have close values with small deviations of ±50 K.
Conclusions
In this paper the efficiency of the method of panoramic measurement of instantaneous temperature fields in a single laser shot based on laser-induced fluorescence of the OH radical when the band (1-0) of the transition A2Σ+–X2Π is excited was tested. Numerical simulations in the commercial LASKIN package show that when the Q1(8) transition is excited, the ratio of the intensity of the fluorescence signals for the band (2-0) and the bands (0-0), (1-1) has a high sensitivity to temperature (namely, higher than 1:5 for the range of 1200-2200 K) and is not significantly affected by fluorescence quenching. The data obtained using the two-line PLIF method and the method, described in this paper, are almost identical, which indicates the reliability of the data obtained using the described method. The proposed method can be effectively used for detecting and registering hot zones in combustion products in the case of laminar premixed flames.

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References
[1] Miller V A, Gamba M, Mungal M G and Hanson R K 2013 Exp. Fluids. 54(6) 1539
[2] Bessler W G and Schulz C 2004 Appl. Phys. B. V. 78(5) 519–33
[3] Devillers R, Bruneaux G and Schulz C 2008 Appl. Opt. 47(31) 5871–85
[4] Kostka S, Roy S, Lakusta P J, Meyer T R, Renfro M W, Gord J R and Branam R 2009 Appl. Opt. 48(32) 6332–43
[5] Heinze J, Meier U, Behrendt T, Willert C, Geigle K P, Lammel O and Lückerath R 2011 Z. Phys. Chem. 225(11–12) 1315–41
[6] Copeland C, Friedman J and Renksizbulut M 2007 Exp. Thermal Fluid Sci. 31(3) 221–36
[7] Bültler A, Lenhard U, Rahmann U, Kohse-Höinghaus K and Brockhinke A 2004 Optical Society of America paper TuE4
[8] Janus B, Dreizler A and Janicka J 2007 Proc. Combust. Inst. 31(2) 3091–8