Temperature measurements in a swirling impinging flame by planar laser-induced fluorescence

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Abstract. This article presents the results of approbation of the method for registering temperature distributions based on the planar laser-induced fluorescence of a hydroxyl radical (OH) when the band (1-0) of the A2Σ−X2Π system is excited. The thermometry is based on the recording the ratio of the radiation intensity of the band (2-0) and the bands (0-0), (1-1). Numerical modelling of fluorescence spectra is performed using the LASKIN program for the most frequent excitation lines Q7(7), Q8(8), R1(14), P2(2). The temperature field of a swirling flame, impinging on a flat cold surface, for H/d = 1, 2 and 3 calibres (where H is the distance between the jet nozzle and the surface, d is the outlet diameter of the nozzle) is obtained. The results of the work demonstrate that when the transition Q8(8) is excited, the ratio of the intensity of fluorescence signals for the band (2-0) and the bands (0-0), (1-1) provides a high sensitivity to temperature and is not significantly affected by fluorescence quenching. The report also concludes that this method can be implemented using single pulsed laser illumination and is effective for the detecting the position of flow recirculation zones and registering hot heat release zones with the combustion products.

1. Introduction
The method of planar laser-induced fluorescence (PLIF) is used to investigate the spatial structure of flows, and is also effective for studying the spatial distributions of radicals, which visualize the zones of chemical reaction and the areas of local heat release [1-3]. The PLIF method is also successfully used for the non-intrusive measurements of temperature field in non-reacting and reacting gas flows, in particular, this method can be used in high-speed [4] and high-temperature flows [5]. The method is based on the registration of the images of the fluorescence intensity of molecules excited to a higher electronic state in the selected flow plane using laser radiation. In flows with combustion, changing the wavelength of laser radiation allows excitation of various types of molecules, which are reactants (hydrocarbons, O2), intermediates (HCHO, HCO, etc.), as well as molecules, which are almost not involved in the chemical reactions (I2, SO2).

Obtaining a 2D temperature distribution by registering the fluorescence of the OH radical is possible by using the intensity ratio for different parts of the spectrum, whose intensity depends on the temperature [6]. In this approach, the flow is illuminated once and the local intensity ratio of two different fluorescence bands is recorded using two cameras. The method is based on the effect of vibrational energy transfer during excitation of molecules, when the levels with energy higher than that of the excited state are populated during collisions with high-temperature molecules. In [6], this approach was tested for temperature measurement in the case of a premixed Bunsen flame for a
mixture of methane and air with different values of the fuel excess coefficient when the transition \( A^2\Sigma^+ \rightarrow X^2\Pi (0-0) \) was excited. The ratio of the local intensity of the images corresponding to radiation of the vibrational bands (0-0) and (1-0) was used to estimate the local temperature in the range of 1700-2200 K with a typical accuracy of \( \pm 100 \) K. Measurements are also possible for the ratio of bands (0-1) and (1-0), but with a much lower signal-to-noise ratio.

The present study focuses on the approbation of the thermometry method based on the OH PLIF when the transition \( A^2\Sigma^+ \rightarrow X^2\Pi (1-0) \) is excited and the ratio of the fluorescence intensity between the band (2-0) and bands (0-0), (1-1) is recorded. The commercial LASKIN software package was used for computer modelling of OH fluorescence [7]. The method was applied to a swirling premixed methane-air flame directed against a flat cooled surface.

2. Experimental setup

The experimental rig consisted of a burner with a profiled contraction nozzle and an internal outlet diameter \( d = 15 \) mm with the possibility of supplying a mixture of methane and air. A blade swirler with swirl parameter \( S = 1 \) was installed inside the nozzle, which corresponded to strong swirl. The equivalence ratio of the methane-air mixture \( \Phi \) was 0.7, the Reynolds number was \( Re = 5000 \). An impinging surface was installed above the nozzle, which was a cylindrical metal vessel, where the temperature was maintained constant. The distance between the impinging surface and the nozzle of the burner device was changed using a coordinating mechanized device. The scheme of the experimental setup is shown in Figure 1.

![Scheme of the experimental setup](image)

**Figure 1.** Scheme of the experimental installation.

The system for measuring the intensity of the PLIF signal of the OH radical 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 electron-optical converters. The laser beam was transformed into a laser knife (the formation of a laser knife is carried out by converting a laser beam into a divergent plane of laser radiation in space using a system of cylindrical and spherical lenses; the thickness of such an area is 0.8 mm, the height is 50 mm) using collimating optics (LaVision). The tunable laser excited OH fluorescence at the transition wavelength \( Q_1(8) \) of the system \( A^2\Sigma^+ \rightarrow X^2\Pi (1-0) \). The average pulse energy with a wavelength of 283 nm was approximately 12 mJ. To take into account the heterogeneity of distribution of the laser radiation energy density in the laser knife and the change in the pulse energy from flash to flash, part of the laser beam energy (approximately 5\%) was reflected by a quartz glass plate into a calibration cell containing a 6G rhodamine solution. The linear mode of fluorescence was tested by changing the energy of laser radiation.

The spatial distribution of the fluorescence signal inside the cell 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 bands (0-0), (1-1) was recorded by two digital cameras with image brightness amplifiers. 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, photocathode S20). The EOP was also equipped with a UV lens and a bandpass filter (265 ± 5 nm). For the bands (0-0) and (1-1), a Princeton Instruments PI-MAX-4 camera (S20 photocathode, 1 Mpix, 16 bit) was used, equipped with a UV lens and a band-pass optical filter (310 ± 10 nm). The frame exposure time for each PLIF image was 200 ns.

3. Results

Numerical modelling and verification of the efficiency of thermometry based on OH fluorescence using the LASKIN software package were carried out in this work. The simulated gas composition of the flame combustion products of the stoichiometric methane-air mixture (fuel excess coefficient, \( \Phi = 1 \)) corresponded to the following molar fractions of \( \text{N}_2 \), \( \text{CO}_2 \), \( \text{H}_2\text{O} \) and OH: 72%, 9%, 18% and 1%, respectively. The OH fluorescence was numerically simulated at excitation of transitions \( Q_2(7), Q_1(8), R_1(14), P_1(2) \) of the band (1-0) of the \( \text{A}^2\Sigma^+ - \text{X}^2\Pi \) system.

![Graph showing the ratio between the integral intensity of OH fluorescence for the spectral ranges of 260-270 nm (I_1) and 300-320 nm (I_2) for different transitions at different temperature values and the effect of oxygen concentration on excitation of the transition \( Q_1(8) \) at different \( \Phi \).](image-url)

Figure 2. The ratio between the integral intensity of OH fluorescence for the spectral ranges of 260-270 nm (I_1) and 300-320 nm (I_2) for different transitions at different temperature values and the effect of oxygen concentration on excitation of the transition \( Q_1(8) \) at different \( \Phi \).
Figure 3 shows examples of the averaged fluorescence signal obtained from two cameras (for \( H/d = 1 \) and 2). The PLIF signal for the spectral range of 260-270 nm (left row) is noticeably weaker than that for 300-320 nm (right row), the processed images for the first case have a significantly lower signal-to-noise ratio, including due to the contribution from scattered laser radiation (this is discussed in detail in [8]). Taking into account the signal received from two cameras, the ratio of these signals to each other and calibration, averaged temperature fields for the selected distances were obtained. Figure 4 shows the results of measuring the average temperature field for a pre-mixed turbulent flame \((\Phi = 0.7, \text{Re} = 5000)\) using OH-PLIF thermometry for \( H/d = 1, 2 \) and 3. The temperature field was estimated from spatially smoothed PLIF data using a 30x30 pixel moving average filter. The sample for each \( H/d \) ratio consisted of 500 images. To convert the ratio of fluorescence intensities to temperature, the calibration obtained for the Bunsen flame was used [8]. The image shows an estimate of the temperature of the combustion products in the range of 500-1500 K.

In the initial images, the maximum intensity of the fluorescence signal is observed behind the flame front at the boundary of the outer mixing layer and the base of the swirling jet. For the case of \( H/d = 2 \) and 3 calibers inside the central recirculation zone between the nozzle and the cooled surface, the fluorescence signal is quite low, in contrast to the case without a surface [9]. The signal distributions for \( H/d = 2 \) and 3 are quite similar, so an example is given for \( H/d = 2 \). For all distances from the nozzle to the surface, a high temperature (more than 1400 degrees) is observed inside the central recirculation zone in the area of its presence. In addition, the temperature inside the recirculation zone without a surface is higher (more than 1800), which is discussed in [10].
4. Conclusion

In this experimental work, the temperature fields of the impinging swirling flame were obtained at three different distances from the impinging surface to the nozzle of the burner device. In this paper, it is concluded that when the transition $Q_1(8)$ is excited, the ratio of the intensity of fluorescence signals for the band $(2-0)$ and bands $(0-0)$, $(1-1)$ provides high sensitivity to temperature (above 1:5 for the range of 1200-2200 K) and it is not significantly affected by fluorescence quenching. It is found that the maximum intensity of the OH fluorescence signal is observed behind the flame front at the boundary of the outer mixing layer and the base of the swirling jet. It is also found that the OH fluorescence signal between the nozzle and the impact surface is significantly lower than in the case without surface and, in general, the temperature inside the recirculation zone is lower than in the case without surface. It is also concluded that this method of temperature registration can be implemented with single pulsed laser illumination and is effective for detecting and registering hot zones in combustion products.

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