Optical diagnostics of hydrogen-air diffusion flame

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Abstract. Work motivation – adaptation of optical Hilbert diagnostic methods for visualization and study of optical density and phase temperature fields in the structure of an axisymmetric diffusion hydrogen-air flame. The diagnostic complex is implemented on the basis of the IAB-451 device with modified blocks of optical filtering, information source and processing. A laminar jet flame $H_2/N_2$ in still air is considered. The investigated torch is oriented vertically. Visualization of phase disturbances induced by the medium under study in a multi-wavelength probing ($\lambda_1 = 636$ nm, $\lambda_2 = 537$ nm and $\lambda_3 = 466$ nm) light field is performed using polychromatic Hilbert and Foucault-Hilbert transformations in combination with registration and pixel-by-pixel processing of the dynamic RGB image structure. The dynamic phase structure of the diffusion flame is visualized. The initial temperature approximation, based on the assumption of an air mixture, is corrected so that the calculated hilbertogram matches the measured one as closely as possible. The data obtained are in good agreement with the results of thermocouple measurements. The temperature was recorded by thermocouples at reference points. The phase function is reconstructed in axisymmetric sections from RGB-hilbertograms. The reliability of the results is confirmed by comparing the experimentally obtained hilbertograms and hilbertograms reconstructed from phase structures using the Abel transform.

1. Introduction

The methods of Hilbert optics and interferometry are one of the directions of non-disturbing diagnostics of reacting jets and flames [1, 2]. The paper [3] describes a method for assessing the temperature distribution in an asymmetric flame using high-contrast stereoscopic photography. The spectral reconstruction of temperature fields using pyrometry of color ratios and interferometric tomography is reported [4]. An example of adapted to the problems of flame research is optical diagnostics based on the methods of Hilbert optics and interferometry in combination with pixel-by-pixel processing of the dynamic structure of visualized phase structures induced by temperature fields [5].

In the combustion of premixed mixtures [6], the refractive index of air can be used to calculate the temperature field. As shown in [7], at a sufficiently large distance from the burner cutoff, in the flow of hot combustion products of the $H_2/N_2$ fuel mixture in air, the approximation of the air mixture also
gives a good accuracy in determining the flame temperature. The aim of this work is to use and improve the optical Hilbert methods for the study of an axisymmetric hydrogen-air flame with the reconstruction of the spatial phase and temperature structure. Research is aimed at solving a scientific and practical problem, which consists in finding methods for controlling the structural and thermodynamic parameters of the torch [8].

2. Experimental research method

The diagnostic complex is based on the IAB-451 optical shading device [9]. Figure 1 shows a simplified diagram of an optical diagnostics complex that implements the method of Hilbert visualization of the medium under study. The complex contains an illumination module consisting of a light source (1) – RGB-LED with operating wavelengths $\lambda_1 = 636$ nm, $\lambda_2 = 537$ nm and $\lambda_3 = 466$ nm, collimator lens (2) and slit diaphragm (3), placed in the front Fourier plane of objective (4), which forms the probing field. The Fourier spectrum of phase disturbances induced in the probing field by torch (5) is localized in the frequency plane of objective (6), where a quadrant Hilbert filter (7) is placed, the orientation of which is matched with aperture (3). The lens (8) performs the inverse Fourier transform of the filtered field, forming, depending on the spectral characteristics of the light source, analytical or Hilbert-coupled optical signals, which are recorded by a digital video camera (9) connected to a computer (10).

The Hilbert transform has the properties of energy redistribution from the region of low spatial frequencies to the high-frequency region. Extrema and gradients of the phase optical density of the investigated medium are transformed into visualized structures of Hilbert bands. The spatial distribution of the Hilbert bands carries information about the perturbations of the phase optical density induced by the temperature field. The fuel mixture was fed vertically into stationary air through a tube with an inner diameter of $d = 5$ mm and a length of 500 mm. The tube material is stainless steel. The experiments were carried out in the range of Reynolds numbers $Re = 1000$–2000. With these parameters, a laminar Poiseuille flow was established in the tube. The composition and consumption of the fuel mixture of hydrogen with nitrogen was set using a program-controlled generator of calibration gas mixtures UFPGS-2. The room temperature was 24.8 °C, the water vapor content in the atmosphere was 0.56%.

The Hilbert image of a hydrogen-air flame obtained during simultaneous shooting at three different wavelengths of the source $\lambda_1 = 636$ nm, $\lambda_2 = 537$ nm and $\lambda_3 = 466$ nm is shown in figure 2(a), the division of the frame into RGB channels is shown in figure 2(b)–2(d).
3. Theoretical background

According to the Cauchy dispersion formula [10, 11]

\[ n_k(\lambda) = A_k \left( 1 + \frac{B_k}{\lambda^2} + \frac{D_k}{\lambda^4} \right), \]  

the refractive index of the k-th component of the burning mixture \( n_k(\lambda) \) depends on the wavelength of the radiation source \( \lambda \) and parameters \( A_k, B_k \) and \( D_k \) which are determined empirically by measurement \( n_k(\lambda) \) for \( \lambda \) three different values. When calculating in formula (1), you can limit yourself to only the first two terms.

The refractive index of the entire mixture (hydrogen-air flame) is defined as

\[ n - 1 = \frac{p}{p_{n.c}} \frac{T_{n.c}}{T} \sum_k A_k \left( 1 + \frac{B_k}{\lambda^2} \right) \cdot C_k, \]

where \( p \) is the pressure; \( p_{n.c} \) – atmospheric pressure under normal conditions (101.325 \cdot 10^3 \text{ Pa}); \( T \) – temperature if jet flame; \( T_{n.c} \) – temperature under normal conditions (0 \degree C).

The method for reconstructing the temperature distribution from the measured values of the refractive index \( n \) is based on equation (2), which relates \( n \) to the temperature and composition of the gas mixture at a point. For flames of hydrocarbons in air, the refractive indices of individual substances differ slightly from each other and therefore, with acceptable accuracy, \( n \) can be considered independent of the composition. A hydrogen flame is distinguished by a wide variety of properties of the components of the gas mixture. In this case, an assessment of the content of the main components \( H_2, N_2, O_2 \) and \( H_2O \) is required.

The phase function of the probing light field passing through the medium under study is defined as

\[ \Delta \psi(x, y) = k \int_{z_1}^{z_2} [n(x, y, z) - n_0] dz, \]

where \( k = 2\pi/\lambda \) is the wave number of the probing field; \( n(x, y, z) \) is the refractive index of the medium in the spatial structure of the flame; \( n_0 \) is the refractive index of the medium (air) undisturbed by the flame. The probing light beam propagates along the \( z \) axis, the torch section is described in coordinates \( x, z \). The choice of the position of the section is determined by the coordinate \( y \). Coordinates \( z_1, z_2 \) set the size of the flame section in the direction of the probing light beam. In the case of axial symmetry of the flame, formula (3) is transformed into the Abel equation:

\[ \Delta \psi(r, y) = 2k \int_{x}^{R} \frac{[n(r, y) - n_0]}{\sqrt{r^2 - x^2}} \frac{r \, dr}{}, \]

\( (4) \)
where \( r^2 = x^2 + z^2 \), \( R \) – cross-section radius of the zone under consideration, \( n(r, y) \) – refractive index at a distance \( r \) from the torch axis. Thus, the total phase shift \( \Delta \psi(r, y) \) for a light beam in cross section \( y = \text{const} \) depends on the refractive index \( n(r, y) \) on the segment \((z_1, z_2)\), figure 3.

**4. Hilbertograms processing**

To solve the inverse problem – reconstruction of the flame temperature \( T \) and molar fractions \( G_k \) of fuel combustion products from the hilbertogram, it is necessary to restore the phase function \( \Delta \psi(r, y) \) from the hilbertogram using the algorithm proposed in [5] and, by solving the Abel equation determine the refractive index \( n(r, y) \) of the medium. Thus, when performing measurements at different wavelengths and using formulas (1)–(2), it is possible to restore the values of molar concentrations of fuel combustion products and, accordingly, the temperature distribution in the flame.

In figure 4 shows graphs illustrating the initial recovery of the phase function \( \Delta \psi(r, y) \) in the section \( y = 6 \) mm from the end of the burner tube for three RGB channels (see figure 2). The red curve shows the phase function in the range from 0 to 30 mm, the blue curve is the cross-section of the experimental hilbertogram in the range from -30 to 30 mm, the black curve is the hilbertogram reconstructed from the phase function. The center of the burner hole corresponds to 0 mm.

The method for determining the phase function \( \Delta \psi(r, y) \) consists in iterative sequential selection of the shape and height of the curve represented by the Bezier polynomial (a special case of B-splines), and the subsequent calculation of the refractive index \( n(r, y) \) using formula (4). Further, for \( n(r, y) \), the hilbertogram is calculated and compared with the section of the experimental hilbertogram. The iterative algorithm is repeated until the points of the local minima of the Hilbert bands on the experimental and modeled hilbertograms coincide. This corresponds to the coincidence of the phase function obtained from the solution of the Abel equation and the real phase function.

At this stage of determining the phase function, it was assumed that \( p_\infty = 100500 \) Pa, \( T_\infty = 24.8 \) °C, \( \varphi_W = 19\% \) (relative humidity in the room), \( A_k \) and \( B_k \) are reference data.

In figure 5(a) shows the initial values of the phase function in the section \( y = 6 \) mm for three RGB channels. In figure 5(b) presents the radial distributions of the refractive index obtained from the solution of equation (4). The maximum value of the phase function is achieved at a wavelength of \( \lambda_3 = 466 \) nm, the minimum is \( \lambda_1 = 636 \) nm, at \( \lambda_2 = 537 \) nm it has an intermediate value, which is displayed in the number of Hilbert bands on the experimental and simulated hilbertograms: for the R-channel – 4 bands, for G-channel – 5 bands, for B-channel – 6 bands (see figure 4).

**5. Verification**

As a verification of the results obtained from the reconstructed phase function, the hilbertograms were calculated and compared with the hilbertograms obtained in the experiment figure 6. Comparing the curves, we see that the points of the local minima of the Hilbert bands on the experimental and modeled hilbertograms coincide. This confirms the reliability of the results obtained for the reconstruction of the radial temperature field \( T \) of a hydrogen-air flame (figure 7) and the radial values
of the molar concentrations $C_k$ of fuel combustion products. The discrepancies in the experimental and reconstructed data are due to the distortion of the axial symmetry of the flame in a real experiment due to the influence of dynamic disturbances in the air surrounding the flame.

**Figure 4.** Initial definition of the phase function $\Delta\psi(r,y)$ in section $y = 6 \text{ mm}$: (a) – R-channel $\lambda_1 = 636 \text{ nm}$; (b) – G-channel $\lambda_2 = 537 \text{ nm}$; (c) – B-channel $\lambda_3 = 466 \text{ nm}$.
Figure 5. Section $y = 6 \text{ mm}$ (radius $r$ from 0 to 30 mm): (a) – initial data of the phase function $\Delta \psi(r, y)$ for three RGB-channels; (b) – initial data of the radial refractive index $n(r, y)$ for three RGB-channels.

Figure 6. Comparison of experimental and reconstructed hilbertograms: (a) – R-channel $\lambda_1 = 626 \text{ nm}$; (b) – G-channel $\lambda_2 = 525 \text{ nm}$; (c) – B-channel $\lambda_3 = 461 \text{ nm}$; the solid line is the section of the experimental hilbertogram, the solid black line is the reconstructed hilbertogram, the dashed line is the reconstructed phase function $\Delta \psi(r, y)$. 
Figure 7. Reconstructed radial temperature field $T$ of an axisymmetric section of a hydrogen-air flame in a 6 mm cross section: crimson curve – reconstructed temperature; black dots are the temperature measured by the thermocouple.

6. Conclusion
Comparing the curves, we see that the points of the local minima of the Hilbert bands on the experimental and modeled hilbertograms coincide. This confirms the reliability of the results obtained for the reconstruction of the radial temperature field of a hydrogen-air. The discrepancies in the experimental and reconstructed data are due to the distortion of the axial symmetry of the flame in a real experiment due to the influence of dynamic disturbances of the air environment surrounding the flame. One of the important advantages of the proposed diagnostic method is the potential to carry out measurements with a spatial resolution of up to a few microns, which makes it possible to resolve the spectrum of scales of the reacting flow up to Kolmogorov.

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References
[1] Dubnishchev Yu N, Arbuzov V A, Belousov P P and Belousov P Ya 2003 Opticheskie metody issledovaniya potokov [Optical Methods of Flow Investigation] (Novosibirsk: Sib. Univ. Izd.) p 418
[2] Dubnishchev Yu N, Lemanov V V, Lukashov V V, Arbuzov V A and Sharov K A 2018 Hydrodynamic vortex structures in a diffusion jet flame Swirling Flows and Flames
[3] Qunxing Huang, Fei Wang, Jianhua Yan and Yong Chi 2012 Simultaneous estimation of the 3-d soot temperature and volume faction distributions in asymmetric flames using high-speed stereoscopics images Applied Optics 51(15) 2968–78
[4] Dreyer J A H, Slavchov R I, Rees E J et al. 2019 Improved methodology for performing the inverse Abel transform of flame images for cilor ratio pyrometry Applied Optics 58(10) 2662–70
[5] Arbuzov V A, Dubnishchev Yu N, Lukashov V V, Sharov K A and Lemanov V V 2019 Optical Hilbert diagnostics of hydrogen jet burning Optoelectron., Instrum. Data Process 55(1) 16–9
[6] Xiao Qin, Xudong Xiao, Ishwar K Puri and Suresh K Aggarwal 2002 Flame Effect of varying composition on temperature reconstructions obtained from refractive index measurements in flames Combust. 128 121–32
[7] Sadrollah Karaminejad, Mohammad Hossein Askari and Mehdi Ashjaee 2018 Temperature field investigation of hydrogen/air and syngas/air axisymmetric laminar flames using Mach-Zehnder interferometry Applied Optics 57(18) 5057–67

[8] Litvinenko Yu A 2017 Sibirskiy fizicheskiy zhurnal [Siberian Physical Journal] 12(3) 83–89

[9] Vasiliev L A 1968 Tenevyye Metody [Shadow Methods] (Moscow: Izd. "Nauka", Main editorial office of physical and mathematical literature) p 400

[10] Hauf V and Grigul U 1973 Opticheskiye Metody v Teploperedache [Optical Methods in Thermal Transport] (Moscow: Mir)

[11] Ioffe B V 1983 Refraktometricheskiye Metody Khimii [Refractometric Methods of Chemistry] (Leningrad: 3rd ed., Rev. L.: Chemistry) p 352