doi: 10.17586/2226-1494-2025-25-5-952-960

Experimental study of the optically transparent gas flow and temperature field using the background oriented Schlieren method

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Abstract
The article presents the results of an experimental study of the flow structure and temperature field in a plume formed above a low-power burner flame. The pulsation and spectral characteristics of the flow at key sampling points were analyzed, which allowed us to draw a conclusion about the nature of the flow at the main points of the jet. It is proposed to use time series of changes in the point displacement field to analyze the spectral characteristics of the flow. In this work, the Background Oriented Schlieren method was used to visualize the flow and determine temperatures followed by post-processing in the program developed during the study. The advantage of this approach compared to the traditional optical Schlieren method is that there is no need for parabolic mirrors as well as the ability to obtain results in digital form convenient for further processing. During the experiment, a special background with randomly located bright dots was placed behind the object of study which was filmed by a video camera. Fluctuations in the medium density caused changes in the refractive indices of the medium, as a result of which the points on the background of the video frames displaced, and the displacements of the points was proportional to the change in the refractive index which in turn is proportional to the density gradient and, accordingly, to the temperature gradient of the medium. The displacement of the points was determined by cross-correlation analysis of each frame in comparison with the frames in the absence of disturbances. Then the displacement field was filtered by a median filter in order to minimize noise and statistical outliers. The filtered displacement field was used to calculate the temperature field, while solving the Cauchy problem for temperature with a known derivative at a point and specified boundary conditions. A set of instantaneous point displacement fields, instantaneous and time-averaged temperature fields was obtained, which allowed us to draw conclusions about the flow structure. At characteristic points of the jet, oscillograms of the displacement value were obtained as well as pulsation spectra with an inertial interval corresponding to the "–5/3" law. The approach proposed in the work allows, in addition to contactless study of the temperature field, also studying turbulent flow pulsations in the case of close to two-dimensional or axisymmetric flows.

Keywords
background oriented Schlieren method, temperature field, spectral characteristics of flow, optical studies of flow, flow structure

Acknowledgements
This study conducted by the Moscow Power Engineering Institute was financially supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. FSWF-2023-0014, contract No. 075-03-2023-383, 18.01.2023).

For citation: Bryzgunov P.A., Pisarev D.S., Zlyvko O.V., Rogalev A.N., Rogalev N.D. Experimental study of the optically transparent gas flow and temperature field using the background oriented Schlieren method. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 2025, vol. 25, no. 5, pp. 952–960. doi: 10.17586/2226-1494-2025-25-5-952-960

УДК 532.5-1/-9

Экспериментальное исследование структуры течения и поля температур оптически прозрачной среды посредством фоново-ориентированного шлирен-метода

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Аннотация

Введение. Представлены результаты экспериментального исследования структуры течения и поля температур в конвективной струе воздуха и продуктов сгорания природного газа, формирующейся над пламенем горелки малой мощности. Проанализированы пульсационные и спектральные характеристики потока в ключевых точках отбора, что позволило сделать вывод о характере течения в основных точках струи. Предложено для анализа спектральных характеристик потока использовать временные ряды изменения поля смещений точек. **Метод.** В работе для визуализации течения и определения температур использован фоново-ориентированный шлирен-метод с последующей постобработкой в разработанной в ходе исследования программе. Преимуществом данного подхода в сравнении с традиционным оптическим шлирен-методом является отсутствие необходимости в параболических зеркалах, а также возможность получения результатов в цифровом виде, удобном для дальнейшей обработки. В ходе эксперимента за объектом исследования, который снимался видеокамерой, помещался фон со случайно расположенными черными точками. Колебания плотности среды вызывали изменения коэффициентов преломления среды, вследствие чего точки на фоне на видеокадрах смещались, причем смещение точек пропорционально изменению коэффициента преломления, который в свою очередь пропорционален градиенту плотности и, соответственно, градиенту температуры среды. Смещение точек определялось с применением кросс-корреляционного анализа каждого кадра в сравнении с кадрами при отсутствии возмущений. Далее поле смещений подвергалось фильтрации посредством медианного фильтра с целью минимизации шумов и статистических выбросов. Отфильтрованное поле смещений использовалось для вычисления поля температур, при этом решалась задача Коши относительно температуры с известной производной в точке и заданных граничных условиях. **Основные результаты.** Получена совокупность мгновенных полей смещений точек, мгновенных и осредненного полей температуры, позволивших сделать выводы о структуре течения. В характерных точках струи получены осциллограммы величины смещения, а также спектры пульсаций, имеющие инерционный интервал, соответствующий закону «–5/3». **Обсуждение.** Предложенный в работе подход позволяет в дополнение к бесконтактному исследованию поля температур также исследовать турбулентные пульсации течения в случае квазидвухмерных или осесимметричных потоков.

Ключевые слова

фоново-ориентированный шлирен-метод, поле температур, спектральные характеристики потока, оптические исследования потока, структура течения

Благодарности

Работа выполнена при финансовой поддержке Министерства науки и высшего образования Российской Федерации в рамках государственного задания № FSWF-2023-0014 (Соглашение № 075-03-2023-383 от 18 января 2023 г.) в сфере научной деятельности на 2023–2025 гг.

Ссылка для цитирования: Брызгунов П.А., Писарев Д.С., Злывко О.В., Рогалев А.Н., Рогалев Н.Д. Экспериментальное исследование структуры течения и поля температур оптически прозрачной среды посредством фоново-ориентированного шлирен-метода // Научно-технический вестник информационных технологий, механики и оптики. 2025. Т. 25, № 5. С. 952–960. doi: 10.17586/2226-1494-2025-25-5-952-960

Introduction

The Schlieren technique is a non-invasive method for measuring the density gradient of an optically transparent fluid. The principle of this technique is based on the fact that changes in the density of the fluid or gas also result in changes in the refractive index of the medium. There is a direct correlation between the density gradient and the change in refractive index gradient, which implies that in regions where there is a density gradient, such as those caused by temperature or pressure changes, light rays may deviate from their initial trajectory and form shadow patterns.

Currently, there are two primary classes of experimental approaches based on this phenomenon: traditional optical Schlieren and Background Oriented Schlieren (BOS) techniques.

The traditional Schlieren method [1] utilizes optical systems composed of a point light source, a subject under examination, a focusing element (either a lens or a parabolic mirror), and a “light knife” (a thin, opaque plate). As light passes through areas with varying optical properties, rays from the point source diverge from their original path, while the remaining rays maintain their course. Next, the light beam either travels through a lens or reflects off a parabolic mirror at a focal point where a light barrier is positioned. This barrier serves to block the majority of the light (known as the illumination), while rays that deviate from the primary trajectory bypass it and strike a screen, resulting in a shadow pattern that reveals the density distribution gradient.

A notable advantage of the conventional Schlieren technique is the exceptional quality of the generated images. The primary drawbacks of the traditional Schlieren technique are: the requirement for the installation of expensive (in the case of larger diameters) optical equipment, and the complexity associated with subsequent data analysis due to its analog nature.

The BOS method, first proposed by Dalziel in 2000 [2], involves the installation of a background behind the subject under study, with points applied in a regular or irregular pattern [3]. When light rays reflected from the background travel through it, similar to the traditional Schlieren technique, they deviate from their initial trajectory. A digital video camera captures the object on the background with dots. In this instance, the deviation of the light rays from their trajectory is manifested as a visual displacement of the background dots in regions of the gradient in the refractive index compared to their position in the absence of perturbations. By using cross-correlation analysis of the acquired video frames, a field of displacement points can be generated that is directly proportional to the gradient in refractive index and, consequently, the density gradient. The main disadvantage of this approach is that the quality of the images obtained is inferior to that of the traditional method, and there is also the presence of noise. Additionally, cross-correlation image analysis is a relatively resource-intensive process.

On the other hand, the benefits of BOS include ease of installation and the ability to obtain digital data after processing in two- or three-dimensional displacement fields (in the case of multiple cameras), which can be utilized to reconstruct the density gradient field [4].

Thus, if the density of the medium within the boundaries of the area being studied is known, it is then possible to reconstruct the density field using a gradient field in the presence of [5]. This, in turn, allows for the determination of temperature, pressure, and species concentration fields under known boundary conditions and an equation of state [6–8]. With further processing, it becomes possible to measure velocity fields [9, 10].

When imaging from multiple angles, it is possible to generate a three-dimensional mass distribution [11, 12]. The visualization of mass gradient fields, known as “numerical Schlieren”, can be employed to validate the results of computational modeling when compared to experimental data acquired using the Schlieren technique and shadow method [13, 14].

A substantial portion of the work centered on the implementation of the BOS approach focuses on the investigation of various flames and the convective plumes that form above them. In [15], the BOS method was used to achieve instantaneous three-dimensional refractive index characterization of unstable natural gas flames from Bunsen burners using a 23-chamber setup.

In [16], the candle flame was investigated in a three-dimensional domain using a setup with 11 cameras. In order to reduce image noise, a background pattern printed on a transparent film illuminated by LEDs, and aspherical and Fresnel lenses were employed to ensure uniform lighting of the background. This resulted in high-quality images of the refractive index and temperature distributions at various time points. Similar findings regarding the visualization of density and temperature fields can be found in [17–19]. Additionally, [14–18] demonstrate the turbulent nature of the flow, which is similar to that of currents in free jets.

However, these studies have not analyzed the spectral characteristics of the currents, specifically the frequencies and amplitudes of pulsations that occur. Nevertheless, since the field of point displacements obtained during image processing when implementing the BOS is linearly related to the density gradient and, consequently, temperature, this field can be considered a passive scalar whose pulsations are associated with those of the velocity field.

As shown in [20], using the example of freely convective flows in a cubic cavity, temperature pulsations are directly linked to velocity pulsations and their spectral characteristics (in terms of fundamental frequencies) coincide qualitatively and quantitatively. Therefore, by employing the BOS technique, it is feasible to acquire not only variable fields but also a spectral analysis of the flows.

The significant advantage of this technique in comparison with analyzing time series of temperature data obtained through contact sensor measurements (the conventional approach) is that it eliminates thermal inertia from the primary transducer (such as a thermocouple), and it is a non-contact method of measurement, as the temperature sensor may cause additional flow disturbances.

The goal of this research is to assess the feasibility of the BOS technique for examining the spectral features of the flow, using a plume formed above a low-intensity burner flame as an example as well as to investigate the structure of this jet.

Research method

The BOS technique was employed to investigate the flow field. The setup is illustrated in Fig. 1. A convective jet of heated gas above a burner flame was captured as the subject of study using an Evercam 1000-16-M high speed camera with a backdrop of a disordered dot pattern. A low-power burner with a nozzle diameter D = 5 mm and gas consumption of 0.1 gram per hour was used. The distances from the background, Z_1, to the subject and from the subject, Z_2, to the camera were 150 and 200 mm, respectively, for a total distance, Z_3, of 350 mm, X_1 width was 90 mm, and height Y_1 was 160 mm. The Cartesian coordinate system was utilized. The resulting images were processed using a Python-based program. OpenPIV was used for cross-correlation analysis. Given a fixed distance between the camera and background and a constant focal length, derivatives of the refractive index were determined as follows:

$$\frac{\partial n}{\partial x} = -K\Delta x, \qquad (1)$$

where n is the refractive index at a point; Δx is the displacement along the x axis; K is the empirical coefficient, $K > 0$.

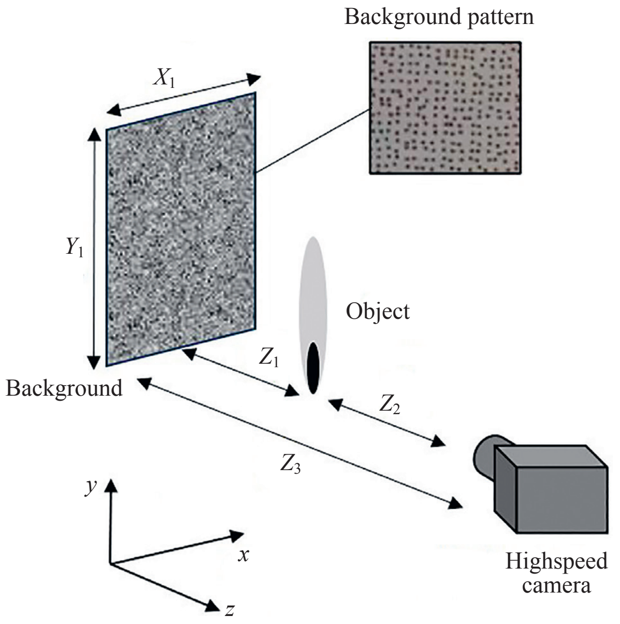

Fig. 1. Experimental setup diagram

The correlation between the refractive index and the density of the medium is linear according to the Gladstone-Dale equation:

$$n - 1 = k\rho, \quad (2)$$

where k is the Gladstone-Dale coefficient and ρ is the density of the medium.

The Gladstone-Dale coefficient for visible light and constant wavelength is dependent on the composition of the medium, but it is independent of pressure and temperature at range below 4000 K [21, 22]. Assuming combustion in air composed of 80 % nitrogen and 20 % oxygen, the volume composition of combustion products from natural gas can be estimated to be approximately 70 % nitrogen, 20 % water vapor, and 10 % carbon dioxide. Under these conditions, the Gladstone-Dale coefficient will vary between approximately $2.3 \cdot 10^{-4}$ m^3/kg for clean air and $2.5 \cdot 10^{-4}$ m^3/kg for combustion products, with a maximum possible change of less than 9 %. Given that combustion, occurs in an open environment, where the combustion products mix with surrounding air, the actual value of the Gladstone-Dale coefficient is likely to be closer to that of clean air. Therefore, a constant value of $2.3 \cdot 10^{-4}$ m^3/kg was chosen for use in this study. Considering equations (1) and (2), the derivative of the density can be calculated using the following equation:

$$\frac{\partial \rho}{\partial x} = \frac{1}{k}\frac{\partial n}{\partial x} = -\frac{1}{k}K\Delta x. \quad (3)$$

The density and temperature (T) of a gas are related through the equation of state:

$$T = \frac{P\mu}{R\rho}, \quad (4)$$

where P is the absolute pressure; R is the universal gas constant (R = 8.3 J/(mol·K)); μ is the molecular weight of the gas.

Since the tests took place in an open volume, the pressure can be assumed to be constant and equal to atmospheric pressure. The molecular weight of clean air is 29 g/mol, and the combustion products of natural gas, taking into account the composition described above, are 27.6 g/mol. The difference is less than 5 %, so μ was assumed to be constant and equal to 29 g/mol. Taking into account these and previously accepted assumptions, as well as equations (1)–(4), the expression for the temperature gradient can be written as follows:

$$\frac{\partial T}{\partial x} = -T^2\frac{R}{\mu P}\frac{\partial \rho}{\partial x} = T^2\frac{R}{\mu P}\frac{K}{k}\Delta x. \quad (5)$$

Thus, in accordance with equation (5), it is possible to determine the temperature field in the presence of boundary conditions by solving the Cauchy problem numerically in a two-dimensional computational domain.

In this study, the equation is solved with respect to the excess temperature; therefore, a zero value is assigned at the lateral boundaries. Due to the fact that the derivative is only taken with respect to x, there is an automatic boundary condition of the second kind, namely, $\partial T/\partial y = 0$, at the upper and lower limits. The empirical coefficient K, which is dependent on the optical properties of the setup, can be determined based on the measurement of flow temperature at a reference point using a thermocouple.

Fig. 2 presents examples of fields obtained during the processing. As illustrated in Fig. 2, *a*, the initial displacement field exhibits substantial noise, as well as artifacts originating from an optically opaque flame. This noise was mitigated through the application of a median filter, as depicted in Fig. 2, *b*. Based on the processed displacement field, the excess temperature field was calculated using equation (3).

It is crucial to note that owing to the inherent opacity of the flame, the temperature gradients within the flame region are assumed to be zero. Consequently, the temperatures displayed in the flame region in the treatment results approximate the closest values of the temperature in the transparent medium.

In order to investigate the oscillatory properties of the jet, we analyzed the displacement values at points *1–4* (Fig. 2, *b*). To eliminate noise during the analysis of fluctuations, we employed a Savitsky-Golay filter [23].

The spectral features of fluctuations with an amplitude Δx were determined using a fast Fourier transform. Given that the acquisition was performed at a constant frame rate, time-averaged fields were obtained by taking arithmetic means of the total instantaneous fields.

Results and Discussion

Fig. 3 illustrates the measurement results for the instantaneous temperature distributions (Fig. 3, *a–c*) and the average field (Fig. 3, *d*). As can be observed in Fig. 3, *a*, *b*, there is a periodic disturbance of vortical structures above the 120-unit mark on the vertical axis. The average time interval between frames indicating the beginning of vortex formation and the end of vortex disruption is approximately 0.1 s, allowing us to estimate a frequency of approximately 10 Hz. The average temperature field clearly reveals a slight

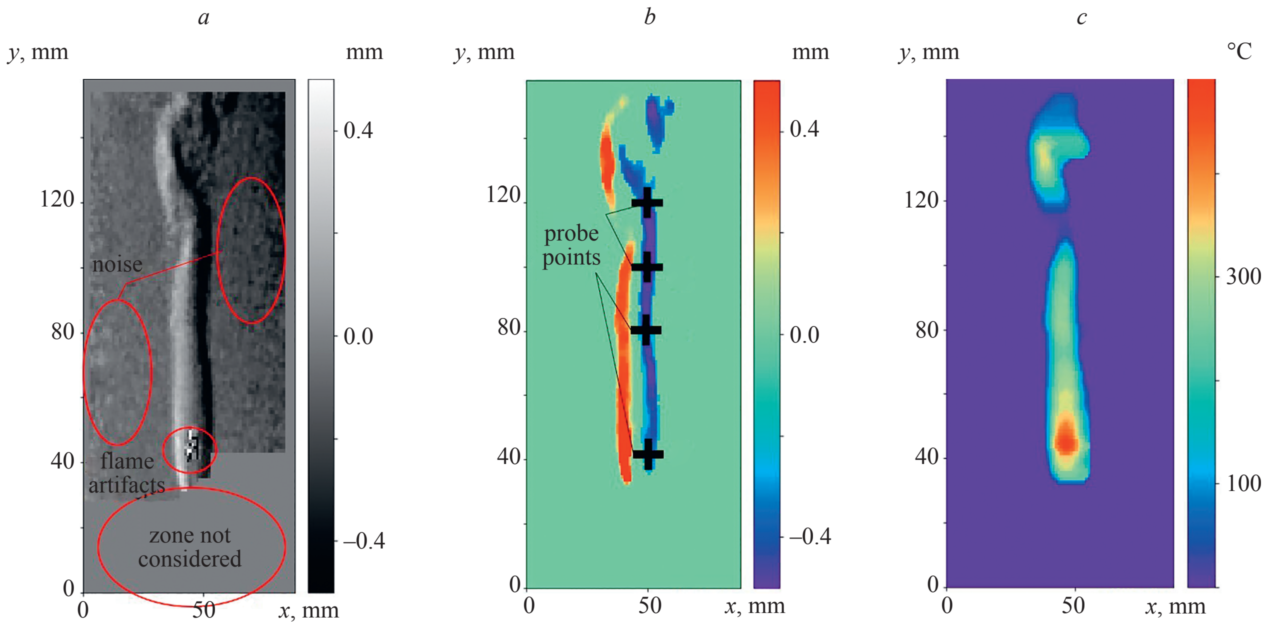

Fig. 2. Examples to the description of the data processing methodology: original displacement field (*a*); filtered offset field (*b*); instantaneous temperature field (*c*)

rightward deviation of the plume which is attributed to the fact that the plume periodically deviates rightward and then leftward in the analyzed dataset, with one additional half cycle occurring in the rightward direction compared to the leftward direction.

As shown by comparing the displacement waveforms at points *1*–*4* (Fig. 4) with the obtained flow patterns, plume oscillations occur every 2.5 s, corresponding to a frequency of 0.4 Hz. The *y* axis coordinate decreases as the sampling points move from *1* to *4*, and the amplitude of the oscillations becomes smaller. The frequencies of these oscillations approximately coincide, indicating a relatively stable, organized flow at point *4*. However, as the height increases, the oscillations become more disordered and chaotic, suggesting a turbulent flow.

An analysis of the average squares of the pulsations at different points (Fig. 5) depending on the *y* axis coordinate allows us to conclude that, on average, the plume decays at height *l* about 12*D*. At the same time, the average pulsation energy increases by more than four times. Thus, an analysis of the results from the perspective of pulsations in the displacement values unambiguously corresponds to the shadow pattern of the currents (Fig. 2, *a*). This allows us to confirm that the proposed approach can be used to analyze turbulence characteristics.

The results of the spectral analysis are particularly interesting (Fig. 6). The pulsation spectra at points *1* and *2* (Fig. 6, *a*, *b*) show typical turbulent spectra, with inertial regions where the amplitude of the pulsations decreases as the frequency increases to the power of "–5/3", in

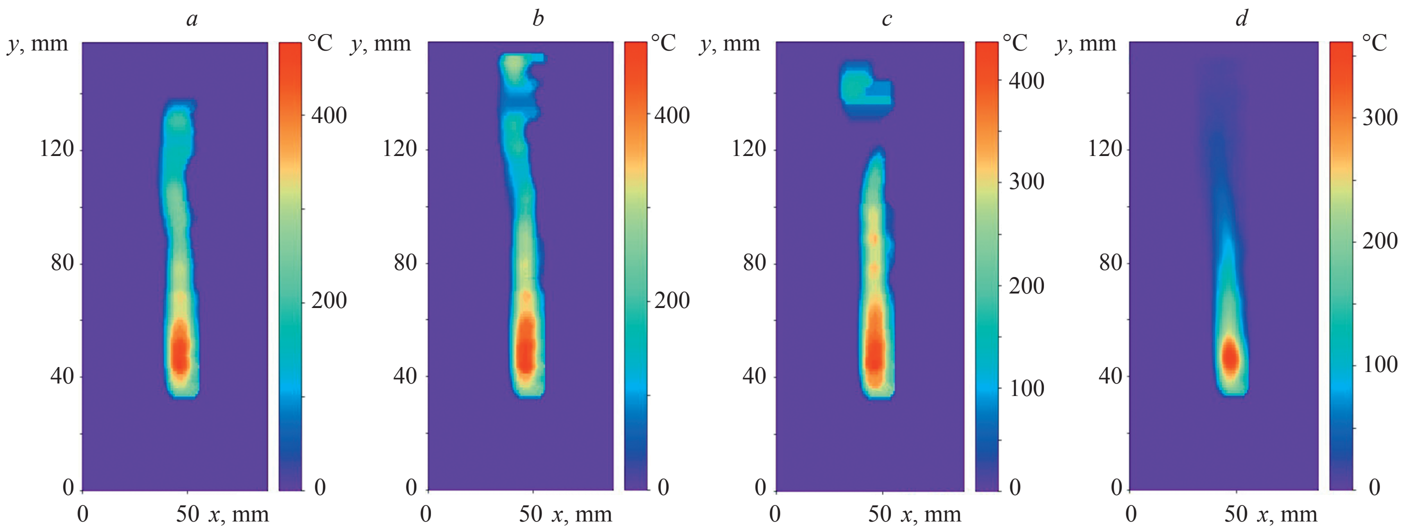

Fig. 3. Instantaneous temperature fields: the vortex formation beginning (*a*); the vortex formation (*b*); the vortex detachment (*c*); and time-averaged temperature field (*d*)

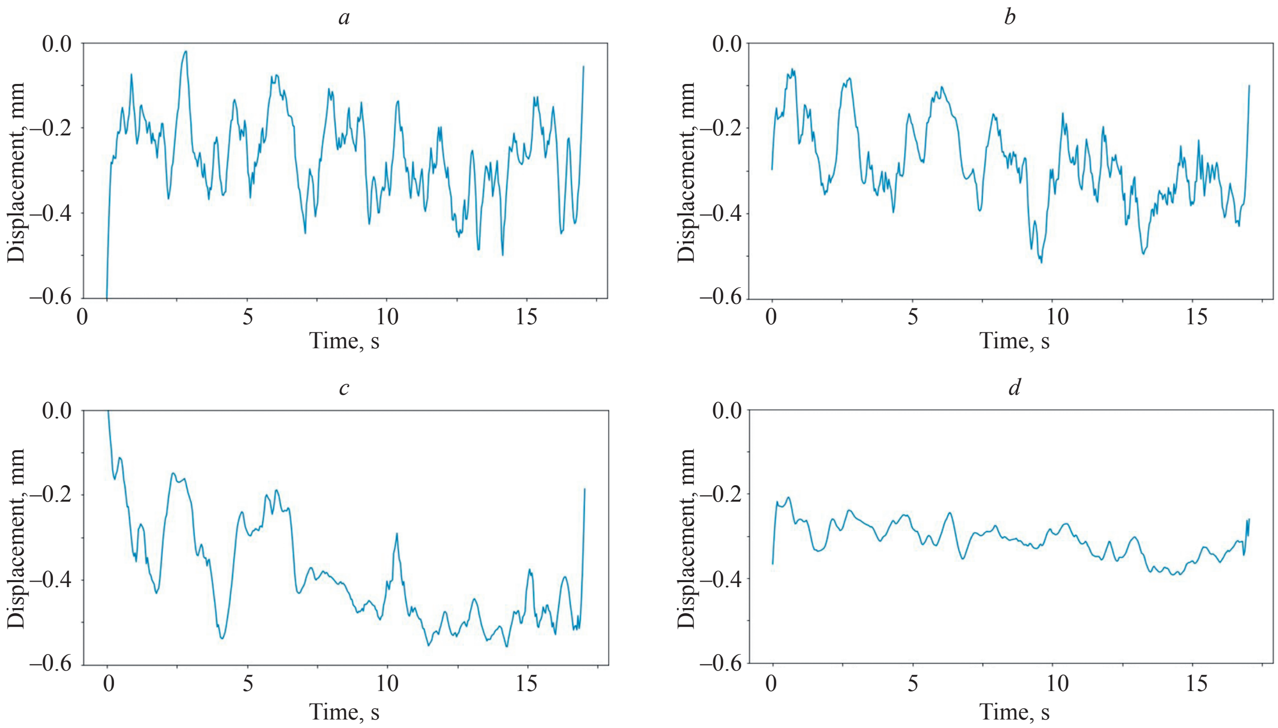

Fig. 4. Oscillograms of instantaneous displacement values at control points: *1* (*a*), *2* (*b*), *3* (*c*), and *4* (*d*)

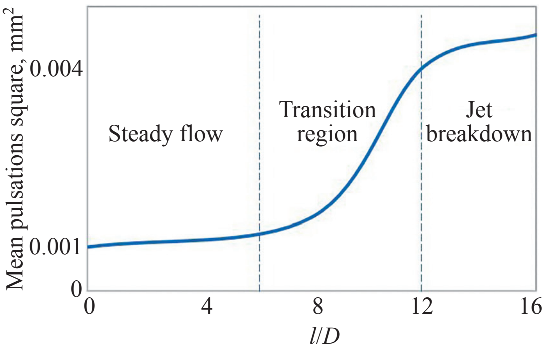

Fig. 5. Dependence of pulsation intensity vs. altitude

accordance with Kolmogorov's "–5/3" law. This confirms the conclusion from the waveform analysis that the flow becomes turbulent at a certain plume height.

At point *4* (Fig. 6, *d*), the spectrum shows a much less turbulent flow, with several peaks corresponding to the frequencies of the most significant pulsations, at approximately 0.4 Hz, 1 Hz, 2.5 Hz, and 10 Hz. The spectrum at point *3* lies between the spectrum at point *4* and those at points *1* and *2*, indicating a transition between these two types of flow. However, both in the case of this spectrum and in the spectra at points *1*, *2*, and *4*, we can easily see the presence of amplitude peaks near the frequencies of 0.4 Hz and 10 Hz. This indicates that these frequencies correspond to the main pulsations of the current.

As mentioned above, the plume oscillates from side to side at a frequency of 0.4 Hz. With a frequency of approximately 10 Hz, vortices form and break up, as was established by analyzing frames of the shadow flow pattern.

Therefore, the spectral analysis of the pulsations of displacement magnitude at characteristic points yields results that are well confirmed by the shadow patterns of the currents. This supports the hypothesis that the field Δx can act as a passive scalar and can be used for non-contact measurement of spectral flow characteristics.

The analysis of the spectral characteristics of the flow can also be performed based on the results obtained from the analysis of instantaneous temperature fields using the BOS method. However, due to the fact that the temperature field is calculated as a numerical solution to a Cauchy problem, there is an inevitable error in the calculation due to the discretization of the grid and the numerical scheme used. This can lead to the loss of a significant portion of the pulsation signals in the analysis.

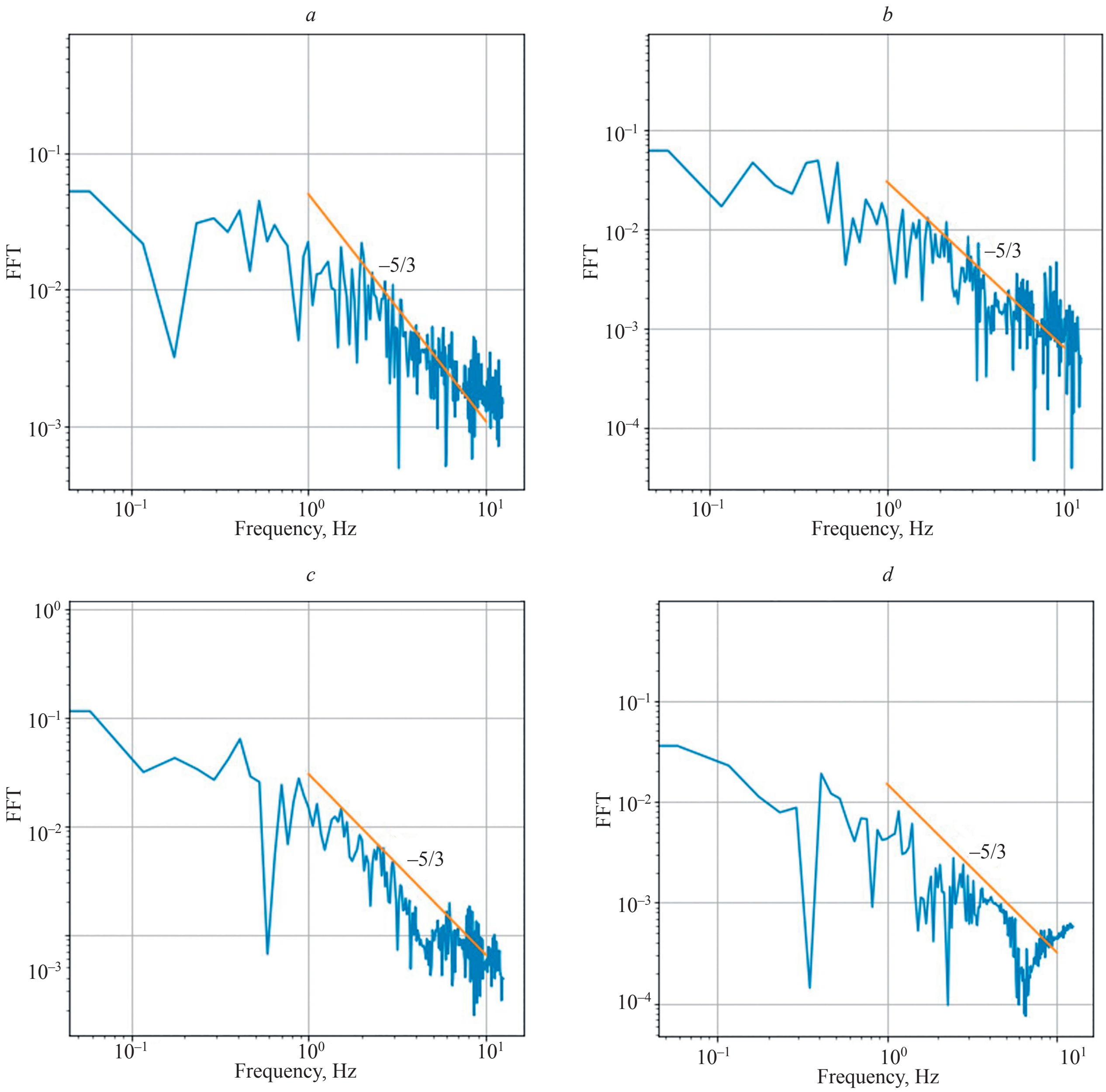

Fig. 6. Results of spectral analysis of pulsations: at points *1* (*a*), *2* (*b*), *3* (*c*), *4* (*d*)

Conclusion

Using the background oriented Schlieren method, shadow flow patterns of a convective plume formed over a laminar diffusion flame of a compact burner were obtained as well as instantaneous and averaged temperature fields.

The flow structure was analyzed and it was found that the plume has a steady flow zone below $l/D = 5$, with a transition region, and the plume disintegrates into separate vortices at $l/D = 12$.

Pulsation and spectral characteristics of the flow at control points were investigated. Spectral analysis revealed the main frequencies (0.4 and 10 Hz) of the flow corresponding to the phenomena observed in the shadow picture frames: the slow oscillation of the plume by x axis and the disruption of vortices in its upper part.

The similarity between the obtained spectral characteristics and the results of analyzing shadow patterns leads us to conclude that the instantaneous displacement fields of points obtained through visualization using the Background Oriented Schlieren method can be used as passive scalars to study flow pulsations non-invasively.

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Received 04.07.2025
Approved after reviewing 31.07.2025
Accepted 15.09.2025

Статья поступила в редакцию 04.07.2025
Одобрена после рецензирования 31.07.2025
Принята к печати 15.09.2025