Investigation of laser radiation propagation through a twisted high-temperature flame jet

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The intensity fluctuations and image jitter of a laser beam propagated through a twisted high-temperature flame jet, as well as fluctuations of the optical radiation emitted by the flame itself, are studied experimentally. Alcohol in an immovable vessel was used as a fuel. In some experiments, the vessel was filled with brass filings. The flame was twisted with a fan, installed over the vessel. The frequency spectra of fluctuations were determined as functions of the fan's speed of rotation.

Introduction

In the recent years, increasing attention has been paid to coherent structures, including, in particular, various spouts and twisted flows.[1–7] References 1–7 consider the results of theoretical and experimental investigations into the physical characteristics of spouts and vortices, the conditions of their formation and stability. At the same time, the medium in such flows is complex and randomly inhomogeneous. The spatiotemporal distributions of the temperature, velocity, and refractive index fluctuate permanently in it. From the viewpoint of fluctuations of the refractive index, these structures can be divided into two groups. The first group incorporates the structures, in which the temperature is close to the temperature of the ambient medium. The structures, in which the temperature far exceeds that of the environment, form the second group. This group is mostly represented by firestorms, which arise in the case of extended and powerful fires.

In this paper we consider a twisted high-temperature flame jet, which is a prototype model of a firestorm. According to the classification from Ref. 1, it is a columnar vortex structure. The model high-temperature structure differs from that considered in Ref. 1 by that the chemical reaction of burning proceeds in its volume. In this case, a large amount of energy (2000–13000 kcal/kg, depending on the fuel) is released and large additional consumption of air (4–17 m^3/kg) is required. Because of the high temperature, high buoyancy force acts in the medium. Conditions for the formation of a firestorm and the stable burning of a fuel in this regime are determined by the twisting force, as well as by the equilibrium between the forces, acting on the medium in the rotating convective column. These forces are: centrifugal force; lifting buoyancy force; force, appearing due to the pressure distribution in the storm (decreased pressure on the storm axis); external forces due to pressure in the ambient medium and the speed of its motion. In the most cases, the motion in these structures has a complex turbulent character, whose investigations are only at the initial stage.

To study the fluctuations of the refractive index of the medium in a flame jet, we applied optical methods, which are used widely in atmospheric investigations.[8,9] In particular, at this stage, we measured the intensity fluctuations and the image jitter of the laser beam propagated through the flame, as well as the fluctuations of the light flux emitted by the flame jet itself. These studies were aimed not only at the determination of the effect of high-temperature medium on the radiation propagation, but also at the development of methods for remote measurements of the optical and physical characteristics of twisted flows and spouts.

Experimental technique and instrumentation

Figure 1 shows block diagram of the experimental setup. A combustible material (20 to 30 ml of alcohol) was poured into an immovable vessel of 142-mm diameter and 17 mm height.

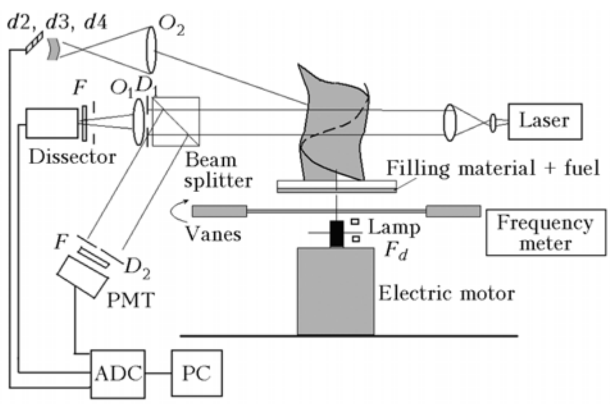

Fig. 1. Experimental setup: interference filters F; diaphragms D_1, D_2; lamp and photodiode of the rotation speed sensor F_d; analog-to-digital converter ADC; personal computer PC; photodiodes $d2 - d4$.

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In some experiments, the vessel was filled not only with the alcohol, but also with a filling material of a porous structure (brass filings) in order to determine its influence on the burning process. An electric motor with a controllable speed was set under the vessel. Vanes, creating the upward twisted airflow around the vessel, were fixed on the axis of the motor. The motor speed was controlled by varying the applied voltage, and the speed of rotation was measured with a frequency meter using the pulses from an optical sensor.

A collimated laser beam (He–Ne laser) of 2-cm diameter propagated through the flame at a height of 10 cm above the level of the burning fluid. The beam-splitting cube split it into two beams. One of thus formed two channels included a PMT with a diaphragm $D_2 = 0.1$ mm. The second channel was equipped with an objective O_1 with an aperture diaphragm $D_1 = 1$ cm, at whose focus a dissector tracking system was installed. This system measured the image jitter of the radiation source along the horizontal and vertical coordinates. An additional objective O_2 formed the image of the flame on three photodiodes, which measured the fluctuations of the light flux in the visible spectral region (0.4–1.1 μm). The photodiodes were arranged horizontally at the height of the laser beam propagation. The information from all the detectors was recorded and processed on a computer. In recording the signals, the sampling rate was 5 kHz, which allowed us to cover a rather wide range of the spectrum of fluctuations. The measurements were carried out in the regime of diffusion burning (no twisting) and with the flow twisting at the rotation speed from 5 to 18 revolutions per second (rps).

Measured results

The processing of the measured results included the calculation of the rms deviation σ and the spectral density of the amplitude of fluctuations of the measured parameters. It is known[8] that intensity fluctuations are sensitive to small-scale inhomogeneities of the field of the refractive index. The maximum of the spectrum is determined by the scales $\sqrt{\lambda L}$ (λ is the radiation wavelength, L is the path length) and the coherence length. At the same time, the fluctuations of the image jitter are sensitive to inhomogeneities of the size equal to or larger than the diameter of the receiving objective.

Figure 2 presents an example of the spectral power density of the fluctuations of image jitter for the laser beam propagated through the flame at the diffusion regime of the fuel burning and at the rotation rate of 17.3 rps.

Analogous examples of the spectra of intensity fluctuations (int) of the laser beam propagated through the flame and fluctuations of the light flux in the flame image at the photodiodes $d2$ to $d4$ are shown in Fig. 3. The spectra shown in Figs. 2 and 3 were obtained with the use of fuel without filling. The addition of a filling material does not change the spectra. It was noticed visually that with the filling material the height of the spout is established more slowly, which is associated with the heat consumption for heating the filling material.

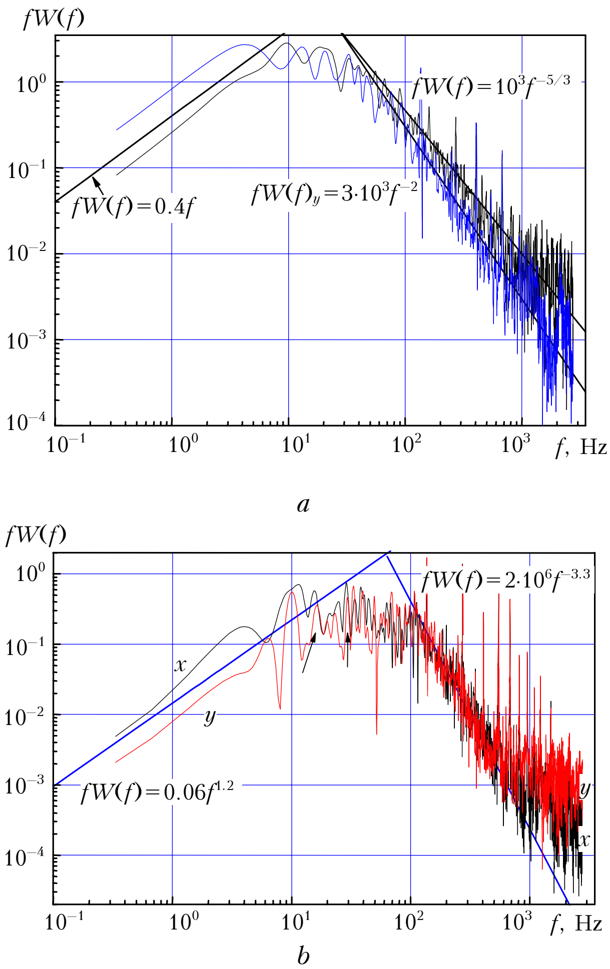

Fig. 2. Spectra of fluctuations of the image jitter of the laser beam propagated through the flame in the regime of the diffusion burning (a) and at the rotation rate of 17.3 rps (b).

It can be seen from Fig. 2a that at the diffusion burning the fluctuations of the image jitter $fW(f)$ in the range of high ($f > f_{max}$) frequencies are proportional to $fW(f) \sim f^{-5/3}$, while in the range of low ($f < f_{max}$) frequencies $fW(f) \sim f$. Such a shape of the spectrum is analogous to the spectra of fluctuations of the laser radiation propagating through the turbulent atmosphere. It should be noted that analogous spectra were obtained in the study of the laser radiation propagation through a convective column over a ground forest fire.[9] In the regime of a twisted jet (Fig. 2b), which begins to establish at the rotation rate higher than 5 rps, the spectra shift to the high-frequency range. The tilt of the spectra in the high-frequency range ($f > f_{max}$) increases $fW(f) \sim f^{-(3-3.3)}$ and almost does not depend on the rotation rate and the presence of the filling material.

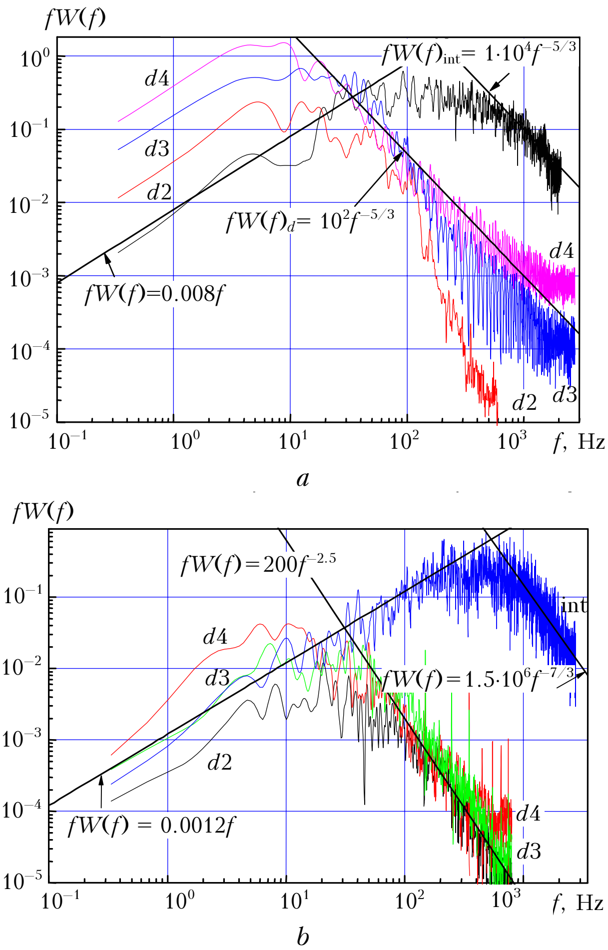

Fig. 3. Spectra of intensity fluctuations (int) of the laser beam propagated through the flame and fluctuations of the light flux in the flame image ($d2$ to $d4$) in the regime of diffusion burning (a) and at the rotation rate of 17.3 rps (b).

The spectra of intensity fluctuations and fluctuations of radiation from the flame show similar behavior (see Fig. 3). The tilt of the spectra of intensity fluctuations even at the initial part of the spectrum at $f \geq f_{\max}$ is $f^{-(2-2.5)}$. To study the shape of the spectra of intensity fluctuations in a more detail, it is necessary to increase the discretization frequency up to ~50–80 kHz. It should be noted that the tilt of the spectra for the radiation emitted by the flame in the range of high frequencies ($f > f_{\max}$) depends on the position of the detector with respect to the flame axis and varies in the range $f^{-(2.3-3.5)}$.

We have also analyzed the dependence of some characteristics of the parameters measured on the rotation rate. Thus, from analysis of the spectra, we have determined the frequencies $f_{\max}$, corresponding to the maximum values of the spectral density $fW(f)$ under different experimental conditions. Figure 4 shows the dependence of the frequency $f_{\max}(x, y)$ of fluctuations of the image jitter and the intensity $f_{\max}(\text{int})$ on the rotation rate n. The straight lines in the figure are obtained by the least-squares method.

The frequency $f_{\max}(x, y)$ of fluctuations of the image jitter increases gradually with the increase of the rotation rate. With the filling material, this dependence becomes steeper. The frequency $f_{\max}(\text{int})$ of the intensity fluctuations increases fast as the rotation rate increases from 5 to 18 rps, that is, the intensity fluctuations are more sensitive to the change in the rotation rate and to the addition of the filling material than fluctuations of the image jitter. This is likely connected with the different sensitivity of the measurement methods to the sizes of inhomogeneities and with the flame structure in different regimes of burning.

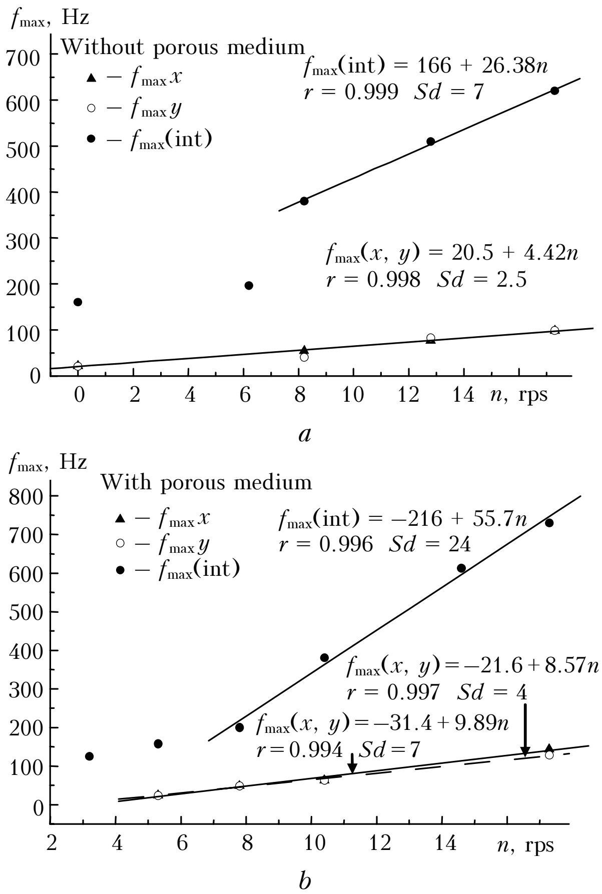

Fig. 4. Frequency of the maximum spectral power density of the fluctuations of the image jitter $f_{\max}(x, y)$ and intensity $f_{\max}(\text{int})$ as a function of the rotation rate n.

In the diffusion regime, the flame structure looks like chaotically appearing sections of vertical turbulent jets, in which the turbulent energy is possibly transferred over the spectrum from large vortices to small ones, down to the scale of dissipation. The flame structure in the twisted jet looks like a system of two and more rotating bunches (Fig. 5) each with its own internal structure.

Figure 6 shows the rms deviation σ of the intensity fluctuations recorded with the PMT (int) and of the light flux recorded with the photodiodes ($d2$ to $d4$) as a function of the rotation rate n for the cases when the vessel with the fuel is filled with the porous medium and without this medium.

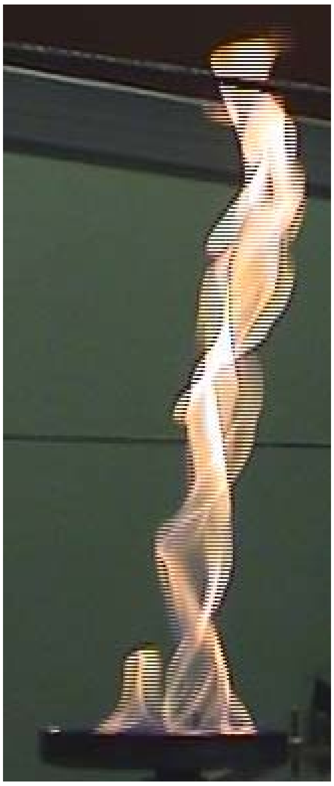

Fig. 5. Twisted flame jet.

It follows from Fig. 6 that the level of intensity fluctuations increases slightly in the regime of the twisted jet at the rotation rate higher than 5 rps. At the same time, the level of fluctuations in the radiation emitted by the flame jet decreases fast, as the rotation rate increases. At the rotation rate higher than 6 rps, it approaches the level of fluctuations of the laser radiation intensity. That is, the level of fluctuations of the flame radiation, which is maximum in the regime of diffusion burning, decreases in the transient regime and changes only slightly in the regime of a twisted jet. The addition of a porous material leads to some increase of the level of fluctuations in the case of burning in the diffusion regime.

Similar shapes of the spectra of intensity fluctuations for the laser beams propagated through the atmosphere and through the flame in the diffusion burning regime suggests that the turbulence in these media is identical. In this case, we can use the equations of the method of smooth perturbations (MSP) to estimate the structure characteristics of fluctuations of the refractive index C_n^2.

The variance of intensity fluctuations in the MSP approximation is determined as

$$\sigma^2 = 1.23 C_n^2 k^{7/6} L^{11/6}, \quad (1)$$

where $k = 2\pi/\lambda$; $L = 12$ cm is the path length in the flame.

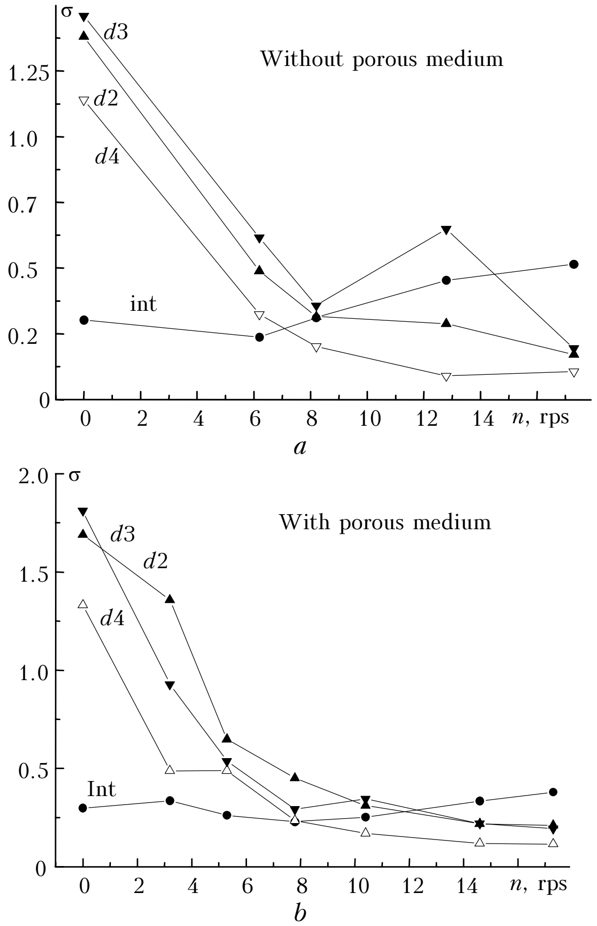

Fig. 6. Root-mean-square deviation σ of the intensity fluctuations (int) and of the light flux recorded with the photodiodes ($d2$ to $d4$) as a function of the rotation rate n.

Using Eq. (1) and the measured values of σ^2, it is possible to estimate C_n^2, which amounts to $\approx(1.4–1.7)\cdot10^{-8}\,\mathrm{cm}^{-2/3}$. Such a value of the C_n^2 is 5 to 6 orders of magnitude higher than the maximum values observed in the atmosphere, where $C_n^2 \approx 5\cdot10^{-14}\,\mathrm{cm}^{-2/3}$ [Ref. 8], and 1 to 3 orders of magnitude higher than the values observed in the convective column above the flame where $C_n^2 \approx 5\cdot10^{-11}–2\cdot10^{-9}\,\mathrm{cm}^{-2/3}$ [Ref. 9].

Conclusions

1. In the low-frequency range ($f < f_{\max}$), the spectral densities of fluctuations of the laser beam parameters $U(f) = fW(f)$ mostly increase proportionally to f.

2. In the high-frequency range ($f > f_{\max}$), the spectral densities of fluctuations of the parameters $U(f)$ decrease proportionally to $f^{-5/3}$ at the diffusion burning and mostly proportionally to $f^{-3.3}$ in the regime of spout.

3. The maximum frequency of fluctuations increases, as the rotation rate of the twisting flow increases. The maximum of fluctuations of the image jitter increases much more slowly than the maximum of intensity fluctuations. The latter starts to increase fast from the time of transition from the diffusion

burning to the burning in the spout mode at the rotation rate of 5.5 rps. The fuel combustion rate behaves similarly, i.e., the amount of the fuel burned per 1 s increases at the rotation rate higher than 5.5 rps.

4. The level of intensity fluctuations varies only slightly as the rotation rate increases, while the fluctuations of the light flux decrease sharply upon the transition into the spout regime.

5. The addition of a filling material to the fuel in the spout regime weakly affects the characteristics of the transmitted radiation, but leads to some increase of the level of fluctuations at the burning in the diffusion regime.

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