Investigation of optical inhomogeneities of a vortex flame

M V Sherstobitov*, V M Sazanovich, R Sh Tsvyk
V E Zuev Institute of Atmospheric Optics SB RAS, 1, Academician Zuev Square, Tomsk, 634055, Russia

*E-mail: shmike@iao.ru

Abstract. On a laboratory scale, a vertical tornado-like flame with a height of up to 1 m and a diameter of the order of 0.05 m was investigated. A laser remote sensing of this flame at several altitudes was carried out. Fluctuations of the self-radiation of the flame in the visible range were recorded at these heights. We calculated the spectral functions of the intensity fluctuations for the probing laser beam and for the fluctuations of the self-radiation of the flame. For these spectral functions, the height dependences of the coordinates of the maxima and the coefficients of the tangent in the high-frequency region are determined.

1. Introduction
In recent years, much attention has been attracted to coherent structures, which include, in particular, various types of tornadoes and swirling flows [1-3]. In these papers, the results of theoretical and experimental studies of the physical characteristics of vortices and tornadoes, the conditions for their formation and stability, are considered. A burning stream is a complex, randomly inhomogeneous medium in which spatio-temporal fields of temperature distribution, velocity, refractive index fluctuate continuously.

In extensive urbanized and natural fires, sometimes a columnar fire vortex appears, a height much greater than during the normal course of combustion. Such a phenomenon, by analogy with the atmospheric tornado, is called a fiery tornado. In the volume of the fiery vortex, chemical combustion reactions take place with the release of a large amount of energy. The conditions for the formation and stable combustion of fuel in the regime of the fire tornado are determined by the twisting force, as well as the equilibrium of the forces acting on the medium. It is known that the effect "pull" of the flame at the twist is widely used in various technical devices to enhance their performance (stabilization of the flame position in the furnace, more complete fuel combustion, etc.).

The motion of the medium in the burning stream has a complex composition, the study of which has not yet been completed [4]. To study fluctuations in the refractive index, optical methods based on the transmission of a turbulent flux by laser radiation can be used [5]. Receiving a passive flame detector is the easiest way to obtain information about the process. The traditional approach to study the fiery tornado is a mathematical and physical modeling. Question fiery tornado simulation using the flame produced by combustion of ethanol in a stationary container, mounted on the axis of the rising swirling air flow, is described in our paper [3]. The question remained of the distribution of the parameters of the spectral functions of the fluctuations of the intensity of the laser beam passing through the model of the fire vortex depending on the height. It was
also supposed to make a comparison with the spectral functions of fluctuations of the intensity of the self-radiation radiation of the flame. A small part of the results on the slopes of the spectral functions of laser radiation was published earlier [6], but in this paper we present these results more fully without averaging for more values of the twist of the air flow.

Thus, the purpose of this study was to determine not only the slope of the spectral functions of the laser beam horizontally crossing the model of the fiery tornado in the diametrical direction, but also to determine the frequencies of the maxima of these functions, as well as the values of the functions at these frequencies. It was supposed to obtain a set of these three parameters for a laser beam and for self-radiation of the flame at several altitudes at different winding speeds.

2. Description of the experiment

Generation fiery tornado model (figure 1) was carried out under the influence of the rising swirling air flow, which was created by the rotating impeller (with eight flat vanes; the inner/outer diameters are 180/320 mm; the angle to the horizon is 20°) on the flame. Fuel is fixed in the ethanol tank, impeller speed was varied from 7 to 17 revolutions per second (rps), and the height of fire tornado models also changed (figure 2), reaching maximum values in the range 10 ÷ 12 revolutions per second. As a fuel ethanol used, its volume in the beginning of all realizations was 20 ml. Capacity diameter was 14 cm, rim height - 1 cm. Thick layer of fuel calculated – 0.17 cm. Ignition of the fuel vapor produced by an external ignition source.

The estimated rate of lowering the fuel level during combustion in our apparatus is ~ 0.11 cm / min. (without impeller rotation), which is comparable with the rate of burning of gasoline.

Laser radiation is very sensitive to optical inhomogeneities, which was used in the study of the environment model fiery tornado. A collimated laser beam (radius 1 cm, wavelength $\lambda = 0.63\ \mu m$) propagated horizontally through the model of a fiery whirlwind. The laser beam was incident on the photomultiplier. Before the photomultiplier a diaphragm with a diameter of 0.1 mm was installed. In addition, an interference filter (GCC 2020: $\lambda_c=632.8\ nm$, $\delta_{0.5}=20nm$) was used in this channel to cut off the radiation from the flame. At the same height as the laser transmission, the photomultiplier detected the self-radiation of the flame of the model of a fiery whirlwind in the visible range, where

![Figure 1](image1.png)

**Figure 1.** The scheme of the experimental setup: 1 - the block for generating a model fiery whirlwind; 2-model of the fiery whirlwind; 3-laser with collimator; 4-photomultiplier with diaphragm; 5-photomultiplier with two diaphragms for receiving self-radiation of the flame.

![Figure 2](image2.png)

**Figure 2.** The height of the model fire tornado, depending on of the impeller speed.
two diaphragms (10 mm and 0.5 mm) isolated a region of diameter ~ 30 mm in the model of the fiery whirlwind. We recorded these signals at 5 propagation heights, a laser beam relative to the fuel tank: 10, 18, 28, 38 and 48 (cm). At each of these altitudes, the combustion patterns were recorded at different rotational speeds of the air flow. All the speed of twist speeds was 7.8, 10, 10.3, 12.2, 12.8 and 13.9 revolutions per second. We were not able to measure for all spin speeds at each altitude (indicated in the table below). Signals from the photomultiplier tube is sampled at a frequency of 12kHz, recorded on a computer. Approximately 500 thousand samples were recorded in each combustion implementation.

3. Results

We calculated the spectral functions of the form $f^* W(f)$. Here $W(f)$ is the spectral density of the FFT signal from the time sequence of pulsations in the intensity of the laser beam, or the self-radiation of the flame, and $f$ is the frequency. Figure 3 presents examples of calculating the spectral function $f^* W(f)$ for fluctuations in the intensity of a laser beam at heights of 10 and 48 cm and for the self-radiation of the flame at a height of 48 cm when the air flow is twisted at a frequency of 7.8 Hz. The example of one spectral function shows how three parameters were determined: the frequency of the maximum $f_{max}$ (Hz), the slope (tangent) in the lg/lg scale in the high-frequency region and the ordinate $f_{max}^* W(f_{max})$ in relative units. Previously, for the function $f^* W(f)$ conducted smoothing results with the procedure used "moving average" 100 values. To optimize processing, instead of manually selecting slope (tangent) coefficients on the lg/lg scale, the author's program was used, in which the slope of the straight line is calculated by the least squares method in the range chosen by the operator.

![Figure 3. Spectral functions of fluctuations in the intensity of a laser beam and the self-radiation of the flame and an illustration of the calculation of three parameters.](image-url)

In the following three figures, 6 graphs with the three parameters mentioned are grouped in pairs for the case of the self-radiation of the flame and a laser beam, and since in addition to the registration height we have the impeller spin frequency, the parameter value is indicated by a symbol indicating the value of rotation. All values obtained at one speed are connected by lines for convenience of perception. Next, in figure 4, the values of the frequencies of the maximums of the spectral functions of the self-radiation of the flame radiation and the values of the frequencies of the maximums of the
spectral functions of the intensity fluctuations of the laser radiation propagating through the model of the fiery whirlwind are presented.

![Figure 4](image_url)

**Figure 4.** The frequencies of the maximum ($f_{\text{max}}$): (a) the flame self-radiation, (b) the functions of laser beam.

It can be seen that the frequencies of the maxima of the self-radiation of the flame correspond to the rotational frequencies of the impeller, and the frequencies of the maxima of the laser radiation functions apparently correspond to the prevailing size of the optical inhomogeneities in the flame. Here we present the flame as a set of burning eddies of different sizes. It can be seen that the frequencies of the laser function maxima increase at medium altitudes, which is probably due to the fact that at these heights the optical inhomogeneities are smaller in size. Next, in figure 5, we calculated the values of the slope of the tangents to the spectral functions.

![Figure 5](image_url)

**Figure 5.** Coefficient of the slope of the tangent to the spectral functions: (a) the flame self-radiation, (b) the functions of laser beam.

The closer to zero the value of the slope coefficient, the more high-frequency components in the spectral function, or in other words more small optical inhomogeneities in the flame. It is seen that as the registration height increases, the optical inhomogeneities become smaller in the functions-a large size (a circle of 3 cm) of the signal pickup region probably affects. In the spectral functions of laser radiation, the growth of optical inhomogeneities with altitude is observed, which, apparently, is associated with the development of turbulence. The coefficients of the slope of the spectra of the self-radiation of the flame are approximately two times higher than the slopes of the laser beam spectra, which is due to the effect of the large spot from which the self-radiation of the flame emitted. According to the theory of Kolmogorov - Obukhov spectrum of refractive index fluctuations in the
atmosphere has a slope "-5/3". But as a model fire tornado is "coherent" structure, and the slopes of the spectral function are different from the said case. Finally, figure 6 shows the values of the spectral functions at the maxima.

![Image](75x523 to 522x674)

**Figure 6.** The values of the spectral functions for (fmax):
(a) the flame self-radiation, (b) of the laser beam (b).

The altitude variation of the values of the spectral functions of the laser beam and its own radiation is directed in the opposite direction. The increase in the values of the spectral functions of the self-radiation of the flame agrees with a corresponding decrease in the slopes - with increasing altitude, a large fraction of the pulsations are concentrated at low frequencies. The similar behavior of all parameters of the spectral functions of a laser beam with maximum values at heights of 28 and 38 cm may be due to the establishment at these altitudes of the most uniform vortex with the largest number of small-scale inhomogeneities.

4. Conclusion
As a result of the study of the three parameters of the spectral functions for the laser beam and for the self-radiation of the flame, we established the altitude variation of these parameters at different twist frequencies. It can be seen that the frequency of the flame rotation can be estimated from the frequency of the spectral maximum of the self-radiation of the flame, even with such a low spatial resolution. With the help of laser sounding, it is possible to obtain a "frequency" portrait of the vortex flame.

Acknowledgements
Authors express their gratitude to Sherstobitov A. M. (Bachelor of Tomsk State University) for writing a program for calculating the slopes of the spectral function.

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