Estimation of the turbulence scale in flame using the method of IR diagnostics

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Abstract

The paper presents the experimental measurements of temperature fields in a narrow mid-infrared spectral range during combustion of different fuels (plant fuels, alcohol, petroleum, kerosene, and diesel fuel). The spectra of temperature changes are obtained in flame. The scale of turbulence in flame is estimated on the basis of temperature nonuniformity measurements and the analysis of temperature spectra in flame.

Keywords: combustion, turbulence, temperature, IR diagnostics

1. Introduction

The studies of combustion processes using IR diagnostic methods have shown that the flame temperature is repeatedly changed in time and the temperature spectra have apparent peaks with different frequencies for different fuels [1]. These frequency peaks are directly related to chemical reactions in flame and the flow regimes. The works [1, 2] state that these temperature fluctuations are connected with the movement of heated regions in flame.

Physical and chemical processes connected with combustion and flame propagation in technological devices and wildland fires take place usually under turbulent conditions [3]. Different parts of the fire front move along with gas at different rates which are composed of averaged and fluctuating components. As a result, the fire front acquires a complicated shape, is chaotically distorted, the surface area of flame increases, which increases the combustion rate of reagents. Turbulent combustion is a nonstationary process of turbulent mixing of the combustion products with a fresh mixture, causing the ignition due to the temperature rise. Under these conditions, the behavior of laminar flame propagation is changed. The decisive factors are turbulent fluctuations and the intensity of turbulent mixing.

Depending on the scale of turbulence and magnitude of turbulent fluctuations, different mechanisms of combustion can be realized in turbulent flows [4]. The model of overall combustion is based on the assumption that the turbulent flame does not differ from the laminar one in the structure [5]. The combustion mode depends on the scale of turbulence. In the case when the scale of turbulence was wider than the reaction zone, Damkeller [6] proposed a flame model that supposed that the flat fire front became distorted and turned into a tangle of laminar fronts under the influence of turbulent fluctuations.

In this mode the laminar flames divide the area into completely burnt and unburned mixtures. The movement of such zones in the flow is accompanied by intense temperature fluctuations and high reagent concentrations.

Despite numerous studies [7-11], the problem of describing turbulent combustion is one of the most difficult problems. Many aspects of this problem are not theoretically and experimentally studied, and still have not reached the level of specification that would allow us to speak with confidence about the complete solution of problem. Answers to questions related to the study of combustion in turbulent flames can be given by the contact-free experimental study of the structure of turbulent flames.

This paper presents the experimental measurements of temperature fields, the temperature spectra in flame and estimation of the turbulence scale according to the frequency temperature spectra and temperature nonuniformity.

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2. Experimental investigation of temperature spectra and estimation of temperature nonuniformity

In the experiments, the system "thermal imager-flame-blackbody" was on the same optical axis, which allowed us to correct the emission coefficient and determine the flame transmission in the spectral ranges under study. The blackbody radiator (45/100/1100, Omsk plant OAO SPE "Etalon") was used as a blackbody model with the temperature range from 573 K to 1373 K. The plant fuels (pine, birch, cedar, pine and cedar needle litter, and field plants) and liquid fuels (petroleum, kerosene, diesel fuel, alcohol) were used as fuels.

The moisture content of plant fuels was 7.9%, the value was determined by the moisture analyzer AND MX-50 with an accuracy of 0.01%. The mass of the layer was determined using an electronic scale AND HL-400 with an accuracy of 0.1 g and was varied from 50 g to 210 g. The air temperature, relative moisture content and atmospheric pressure were controlled by the meteorological station Meteoscan RST01923. The air temperature was varied in the range of T_e = (288-293) K. The relative moisture content was varied in the range of φ = (20-35)%, atmospheric pressure P_e = (9.4·104-1.02·105) Pa.

The flame radiance, blackbody models and temperature distribution were recorded by the thermal imager JADE J530SB with a narrowband optical filter and the spectral range of 2.5-2.7 microns selected on the basis of the emission flame spectra and recommendations [12], which allowed us to measure the temperature in the range of 583- 1773 K with a recording frequency of 170 frames / sec. The recording was conducted by a camera lens with a focal length of F = 50 mm and the 320x240 pixels matrix of the thermal imager. The distance from the thermal imager to the blackbody was 3 m, and the distance from the thermal imager to the center of flame was 2 m. In addition, the flame temperature on the axis of blackbody was controlled with the type tungsten-rhenium thermocouples 50 mm in junction diameter for the time constant ε = 0.09-0.1 s. The flame temperature is additionally controlled by the thermocouples and the average value of the emission coefficient ($\varepsilon\lambda$) was corrected according to the data of the thermocouples. After ignition and appearance of flame, the aperture of blackbody was closed by a screen to eliminate the influence on the combustion process and the recording of flame and compare the results of measurements with the influence of blackbody and without it.

Furthermore, the temperature of flame was found to change multiply in time and has a certain spectrum with characteristic frequency peaks for each fuel type (Fig. 1). These fluctuations are caused by the turbulent flow in flame and have a direct connection with the turbulence scale that can be calculated from the temperature spectra in flame. It should be noted that processing of thermograms allows us to identify temperature nonuniformities in flame, the movement of which causes temperature fluctuations (Fig. 2) and their sizes are consistent with the theoretically calculated scales of turbulence in flame.

To estimate the dimension of temperature nonuniformities, the thermograms were processed frame by frame. Well-expressed flame temperature nonuniformities were selected in each frame and their dimensions were determined using the Altair software. Fig. 2 shows large flame temperature nonuniformities, using as an example the flame produced during combustion of alcohol and cedar needles, and instruments to determine their geometric dimensions. Since temperature nonuniformities are incorrectly shaped and vary in dimension and shape in time, the final measurement of temperature nonuniformities is averaged at a certain moment of time in several measured directions.

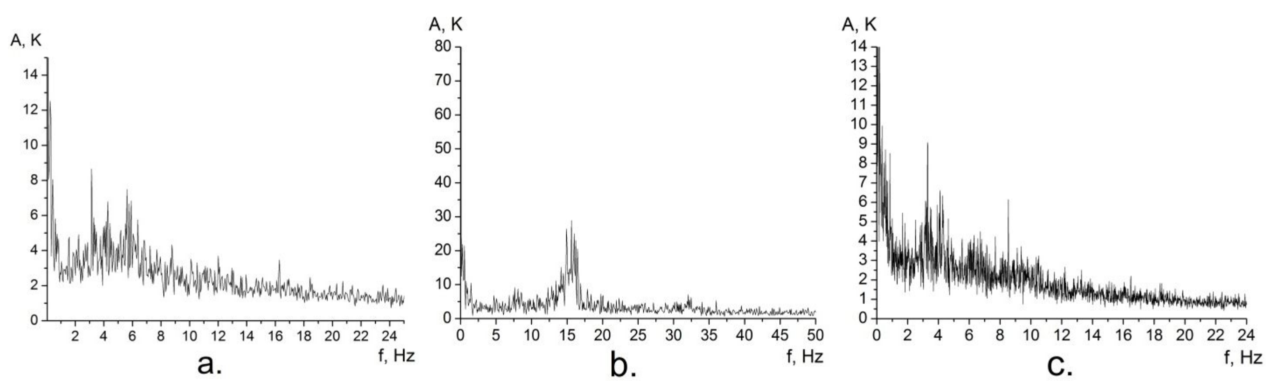

Fig. 1. Temperature spectra in flame of plant fuels (a), alcohol (b), petroleum (c).

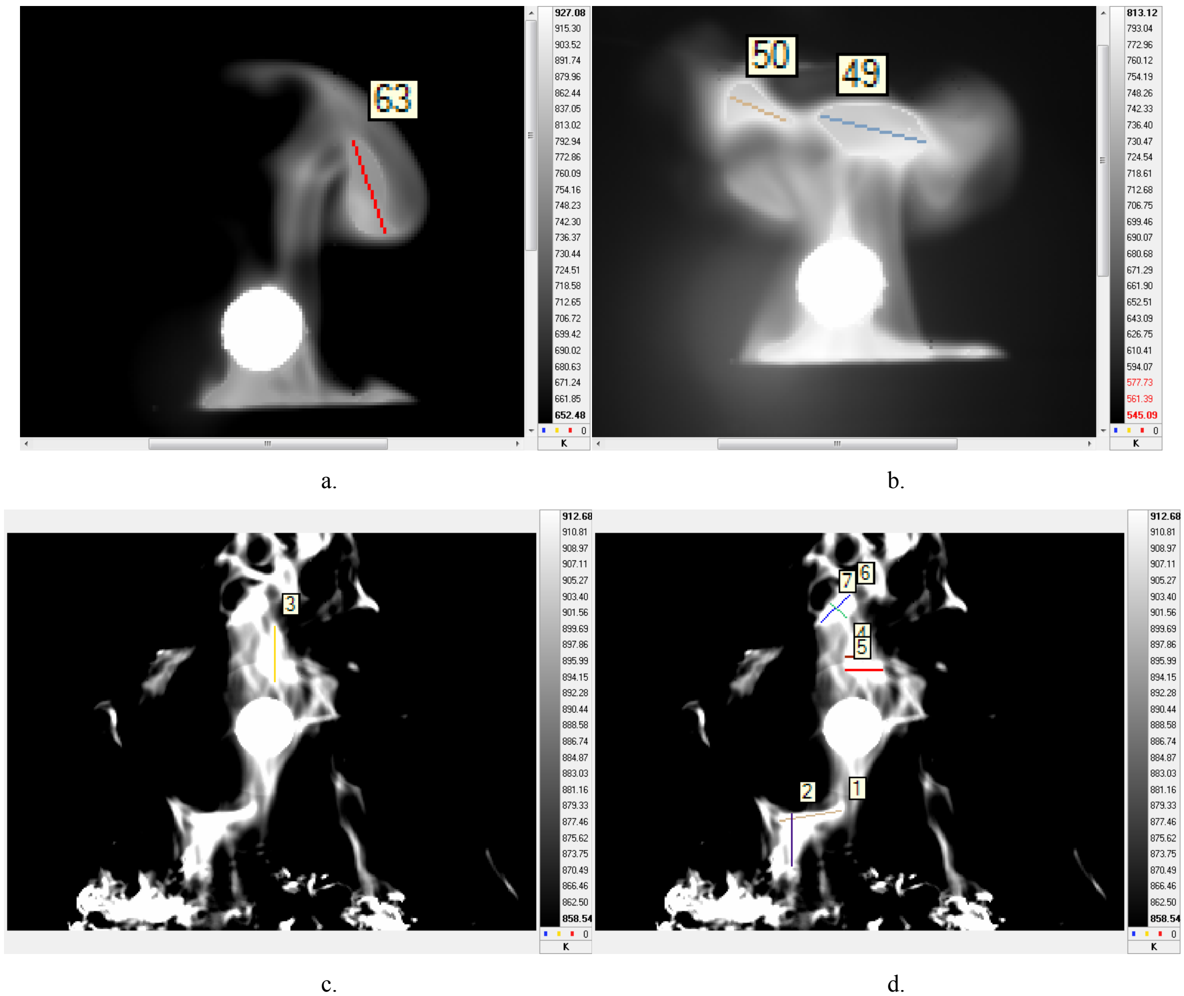

Fig. 1. Dimensions of temperature nonuniformities in flame formed during combustion of alcohol (a, b) and cedar needles (c, d).

3. Theoretical estimations of the scale of turbulence in flame

During thermal decomposition and evaporation of condensed fuels, a nonisothermal ascending flow is formed from a mixture of combustible gases which are mixed with atmospheric oxygen to form the flame. The initial part of the flow is characterized by the predominant influence of the Archimedes force that contributes to the increase in flow rate. When the flow starts cooling, the role of the Archimedes force becomes negligible and the flow moves by inertia and gradually decelerates due to viscous forces. Therefore, this part of the flow can be defined as inertial. Air masses which are the part of flame are mixed with environment.

The stationary flame gradually dissipates and stops existing. The accelerated movement of a less dense hot media in the more dense cold media leads to the hydrodynamic and thermal instability, the growth of turbulent stresses and the formation of turbulence. To estimate the parameters of turbulence in flame in a first approximation, the following approach can be used. Fields of fluctuating velocity components are similar to each other at all points in the flow according to the hypothesis of T. von Karman [13] and differ only in the scale of time and length. Instead of the time and length scales we can use the scales for the frequency of turbulent fluctuations and specific kinetic energy of turbulent fluctuations (turbulent kinetic energy). Turbulence of flame is characterized not only by fluctuations of the velocity and pressure, but also by fluctuations of the temperature and composition of the burning mixture. Since these processes are interconnected, we assume that the frequencies of turbulent fluctuations for hydrodynamic f_D and thermal f_T parameters coincide in flame: $f_D = f_T = f$.

Thus, the frequency of turbulent fluctuations in flame can be determined from experimental data processing that is described in section 2 of this paper. From the similarity hypothesis for fields of temperatures and velocity fluctuations, the following ratio can be written

$$\frac{\langle u_i' u_i' \rangle}{\langle T' T' \rangle} = \frac{U^2}{T^2} . \tag{1}$$

From the formula (1) it follows that the average squares of pulsating velocities and temperatures are related to each other as the squares of the averaged velocities and temperatures.

To characterize the intensity of turbulence in flow, the parameter Tu is commonly used and represents the ratio of the turbulent kinetic energy to the kinetic energy of the overage flow: $Tu = 2k/U^2$. The parameter value $\mathrm{Tu} < 0.05$ corresponds to low turbulence, $0.05 < \mathrm{Tu} < 0.2$ corresponds to moderate turbulence, $0.2 < \mathrm{Tu} < 0.5$ corresponds to high turbulence. Using the ratio (1), the intensity of turbulence in flame can be estimated as:

$$\mathrm{Tu} = \frac{2k}{U^2} = \frac{\langle T'T' \rangle}{T^2} . \tag{2}$$

To determine the turbulent kinetic energy of flame, it is necessary to know the kinetic energy of the overage flow. For this purpose the condition of the energy balance is used. The chemical energy of combustion is transformed into kinetic energy of superheated ascending gases, which in turn is transformed into potential energy of flame:

$$\frac{\rho U^2}{2} = \rho g L , \tag{3}$$

where L is the flame height.

The scale of turbulent vortices, where microvolume gas combustion takes place, displayed in the thermograms as the temperature nonuniformity is determined as follows:

$$b = \frac{\sqrt{k}}{f} = f^{-1} \frac{\sqrt{\langle T'T' \rangle}}{T} \sqrt{gL} . \tag{4}$$

4. Comparison between experimental measurements and theoretical estimations of the turbulence scale

Table 1 represents the theoretical estimations of the turbulence scale in flame and the measurements for the dimensions of temperature nonuniformities in flame.

Comparing the values of b and bexp, given in Table 1, it is seen that the average dimension of temperature nonuniformities almost coincides with the theoretical estimation of the turbulence scale, however, the scattered results of the measurements as compared to the theoretical calculations are caused according to the authors by the fact that the thermograms are processed by using two-dimensional images, but temperature nonuniformities are three-dimensional and change dimensions in all directions during movement in flame.

Table 1. Comparison between experimental measurements for the dimensions of temperature nonuniformities and theoretical calculations for the scale of turbulence according to the temperature spectra.

Type of fuel	**L (m)**	**f±f (Hz)**	**b±b (m)**	**b_{exp}±b_{exp} (m)**
Alcohol	0.3	16±1	0.0032±0.0002	0.0033±0.0015
Petroleum	0.7	4.8±0.8	0.025±0.005	0.024±0.004
		8.6±0.5	0.014±0.001	0.015±0.003
Mixture of plant fuels	1.2	3.2±0.2	0.049±0.003	-
		4.5±0.5	0.035±0.004	-
		5.8±0.5	0.027±0.002	0.018±0.008
pine	1.2	4±1	0.051±0.01	-
		7±0.1	0.029±0.004	0.011±0.007
birch	1.2	5±1	0.036±0.007	-
		10±0.5	0.017±0.002	0.017±0.002

It should be noted that during the processing of the thermograms, the small temperature nonuniformities were well expressed and corresponded to the frequencies in the spectrum of the temperature changes from 6 Hz, and larger temperature nonuniformities in some cases could not be measured due to "smearing" of borders. Dashes in Table correspond to this situation.

Based on the foregoing information, it can be concluded that to estimate the turbulence scale of chemically reacting gas, the thermography methods can be used to obtain the spectrum of temperature changes in the media under study and the estimations of the turbulence scale can be given using the obtained spectrum and the relations given in this paper.

5. Conclusions

1. The temperature in flame changes multiply in time and the temperature spectrum of flame has characteristic frequency peaks caused by the turbulent flow; there is a relationship between temperature nonuniformities and the scales of turbulence.
2. The dimensions of temperature nonuniformities obtained using the methods of thermography correlate with the scales of turbulence obtained on the basis of temperature spectra.
3. Microvolume combustion in turbulent vortices is the main mechanism of fuel combustion according to the Spolding hypothesis.

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