Investigation of the turbulent structure in a flame and the effect of small infrasonic exposure on it using IR thermography methods

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Abstract. The paper presents the results of studies of gasoline and diesel fuel diffusion combustion using IR thermography methods. Experimental results of the effect of small amplitude pressure pulsations with various frequencies on the spectra of temperature changes in the flame and other characteristics are obtained. It is shown that the effect of pressure pulsations with certain frequencies leads to a change in the flame height, fuel burning-up rate and the appearance of characteristic frequency maximum in the spectra of temperature changes in the flame.

1. Introduction
Fuel combustion is a complex of physical and chemical processes that cause the formation of gaseous combustible components and intense heat release. The most common combustion mode is a diffusion combustion, which occurs under turbulent conditions [1]. Diffusion turbulent combustion is an unsteady process of turbulent mixing of fuel vapor products with an atmospheric oxidizer and the ignition of a combustible mixture due to a temperature increase. Depending on the turbulence characteristic and scale, various combustion mechanisms are possible [2]. The flame structure is investigated using various methods. For example, the gas composition and its change in different areas of the flame is determined by probe sampling of gas samples from different flame zones with their further analysis. Placing sampling probes and thermocouples in the flame results in disturbances in the flow and heat balance. In addition, chemical reactions can occur on the measuring device surface, in particular, the recombination of radicals. These perturbations lead to the distortion of the velocity profiles, temperature and compounds concentrations in the flame front and, thus, become the cause of a systematic measurement error, which cannot be excluded. The similar situation occurs while measuring the temperature in a flame using thermocouples and other contact measurement methods.

The advantages of using noncontact methods for flame diagnostics are obvious: infrared thermography and PIV (particle image velocimetry). The PLIF (planar laser-induced fluorescence) method is also used to visualize turbulent structures in a flame [3, 4]. The use of PLIF methods for
recording the temperature fields of turbulent unsteady flames, according to the authors opinion, yields a little information, since it does not allow one to record at rates comparable to the temperature pulsation rate in a flame. The use of PIV methods has a similar disadvantage. Due to the fact that PIV allows one to visualize the velocity field, the use of PIV is advisable for analysing the characteristics of turbulent flow in a flame. The papers [5, 6] present the results of studying the flow structure in flames using PIV. The distribution of flow velocities, streamlines and temperature instability in a flame during combustion of hydrocarbon fuels is discussed in [5, 7].

The use of infrared thermography methods due to modern technical capabilities and high registration rate is a promising direction in the study of the turbulent flame structure and is widely used [7-11]. It should be noted that the use of IR thermography methods for the study of combustion processes is associated with a number of fundamental and methodological difficulties, such as the analysis of emission spectra and optical characteristics of the flame, the choice of the spectral range, etc. [12, 13], since a flame has a high temperature, randomly inhomogeneous, selectively emitting medium.

It should be noted that despite significant long-term studies of turbulent combustion [6, 14-19], which have been conducted in the world since the middle of the 20th century, it is not possible to stand about the completion of studies of this phenomenon. The issue of the relationship and similarity of pulsations of hydrodynamic and thermodynamic parameters remains open, which is formulated at the level of a hypothesis. The data [18] are given on the similarity of these parameters depending on the Schmidt number. Turbulence processes and internal scales have a significant effect on the transfer coefficients [20] and the combustion process in general [21-23], as well as on the propagation of the flame and its structure [24]. The dependences of the flame characteristics on the turbulent Reynolds, Richardson and Stanton numbers are given in [24].

This paper presents the experimental study concerning the infrasound effect on the spectrum of the temperature change in flame and change in the mass of fuel during the combustion of gasoline. The paper is structured as follows: in section 2 features of using IR thermography where the importance of choosing the spectral interval of the study are described; in section 3 describes the experimental setup; in section 4 describes the main results of the study; in section 5 presented the conclusions derived from analysis of thermograms, obtained spectra of temperature and fuel mass changes.

2. Special aspects of using IR thermography

It is obvious that the use of IR thermography methods for measuring the temperature field in a flame is associated with a number of fundamental and technical difficulties. An analysis of the emission spectra of a flame during the combustion of liquid fuels (gasoline, kerosene, diesel fuel), a number of solid plant combustible materials and pure gas (propane-butane) is given in [12]. An analysis of the flame emission spectra and comparison with the emission spectrum of the model of an absolutely black body (ABB) leads to the fact that the study of temperature fields in the flame has to be carried out in the mid-wave infrared range of wavelengths. Narrow spectral intervals should be chosen depending on the solved problem. It has to be considered that, due to the specific of gaseous combustion products emission, the emission spectrum of the flame contains emission bands of CO and CO2 with wavelengths from 4 to 5 μm, and the intensity of this radiation exceeds the intensity of emission from the blackbody at these wavelengths. Therefore, the use of the spectral interval from 4 to 5 μm for the study of combustion processes is nonphysical. The spectral interval 2.5 - 3.0 μm has a greater interest for flame studies. This spectral range contains high emission bands of water vapor formed during combustion. The emission intensity of water vapor does not exceed the emission intensity of blackbody in this spectral range. This allows one to correct temperature measurements in the flame. In the spectral range from 3 to 4 μm, there is radiation from condensed combustion products (soot, smoke particles). Despite the fact that the emissivity of condensed combustion products is close to the blackbody, the flame radiation intensity in this spectral range is not high enough for correct measurements, which is associated with a relatively low concentration of condensed combustion
products in the flame. In the case of clean fuels during stoichiometric combustion (propane-butane, ethanol, pure gases), condensed combustion products are absent. In the wavelength range of 3 – 4 μm there is a transparency window, which allows one to study the temperature of objects in a flame or shielded by a flame.

After the problem of choosing the spectral interval has been solved, the following technical difficulty arises. Specifically, the temperature in the flame changes many times over time and is accompanied by pulsations in case of unsteady diffusional combustion. The spectra of temperature changes in the flame are presented in [13]. It follows from the analysis of the temperature pulsation spectra that an IR camera with a record speed of at least 16 frames per second is required for accurate measurement of instantaneous temperature fields in a flame. This significantly limits the choice of a measuring device along with the choice of the spectral interval of studies. Such devices can only serve as "scientific grade" infrared cameras that allows one to use the narrow-band filters and have sufficient speed. Temperature pulsations in the flame are directly related to the physical and chemical processes occurring in the flame, the cyclicity of these processes and the evolution of turbulent structures [10]. A comparison of turbulent structures in a flame presented in [11], which is visualized using IR thermography and PIV methods. Obviously, there is a similarity of structures in the field of hydrodynamic and thermodynamic parameters, which confirms the hypothesis on the basis of which the scale of turbulence in the flame is estimated in [10].

Summarizing, one can conclude that it is of great interest to study changes in flame characteristics under external exposures of harmonic pressure fluctuations of small amplitude with frequencies close to the frequencies in the spectrum of temperature changes.

3. Methodology

Gasoline was used as a combustible material. The mass of the fuel was 10 g. The recording equipment was a JADE J530SB infrared camera with a narrow-band filter with a passband of 2.5 – 2.7 μm wavelengths. The infrasound generator was a 25-GD-26 low-frequency loudspeaker with a soft suspension. A sinusoidal signal formed by a G6-28 signal generator of a special form was delivered on it, preliminarily amplified with an LV 103 amplifier (figure 1). Additionally, the flame temperature was controlled by a K-type thermocouple to find the effective emissivity of the flame.

![Figure 1. Experimental setup: 1 – Weight scale An A&D GF-3000; 2 – heat insulating pad; 3 – fuel tank; 4 – infrasound generator 25-GD-26; 5 – infrared camera JADE J530SB; 6 – signal generator of a special form G6-28; 7 – amplifier LV 103; 8 – personal computer.](image)

The fuel was combusted diffusively in a container 0.15 m in diameter. The recording equipment was placed at a distance of 1.5 m. The distance from the source of oscillations to the flame was 0.3 m.

The resulting thermograms were processed using the Altair software. The spectra of temperature changes in the flame were obtained using the TempSpectrum-v.1 software.

Figure 2 shows the spectrum of temperature changes in the flame while burning gasoline in the absence of external exposures. It should be noted that for this fuel characteristic frequency maximum can be distinguished in the range of 3.5 - 4.5 Hz.
Figure 2. Spectrum of temperature changes in a flame formed during diffusion combustion of gasoline without external exposures.

4. Investigation results
Subsequently, the flame was exposed to infrasound with frequencies: 2 Hz, 4.1 Hz, 4.6 Hz, 5.2 Hz, 6 Hz 8.5 Hz. Figure 3 shows the corresponding spectra of temperature changes.
It should be noted that the height of the flame plume changed with the presence of infrasonic exposure (figure 4). Also changes appeared in the spectrum of temperature changes, shown in figure 2 and figure 3. Changes in the amplitude are observed at characteristic frequencies. They are clearly visible in the absence of disturbances. In this case, the spectrum of temperature pulsations in the flame changes as a result of the influence of infrasound. It was also noted that exposure to infrasound with a frequency of more than 2 Hz causes the appearance of local amplitude maximum in the spectrum of temperature changes with an exposure frequency [25–26].
Figure 4. Averaged thermograms of a gasoline flame under infrasonic exposure (a – without exposure; b – 4.6 Hz, c – 5.2 Hz, d – 8.5 Hz).

To analyse the change in the mass of gasoline during its combustion, an additional study was carried out on the loss of the mass of fuel with time under external exposure with different frequencies. An A&D GF-3000 weight scale was used for measurements, which allows one to register the change in mass with an accuracy of 0.01 g and a frequency of 5 counts per second (figure 5).

Figure 5. Change in gasoline mass during combustion.
5. Conclusion

The experimental results of diffusion combustion of gasoline and diesel fuel show that external exposure by pressure pulsations of small amplitude with frequencies of 2 – 10 lead to an increase in the flame height to 50 mm. In addition, the effect of pressure pulsations on the flame leads to a change in the rate of fuel burnup (figure 5) and the appearance of characteristic frequency maximum in the spectrum of temperature changes in the flame (figure 3). These effects are caused by the fact that external exposures by pressure pulsations change the turbulent structure of the flow in the flame. It appears in a change of the temperature pulsation spectrum in the flame, which leads to a change in the mixing of combustible gaseous components with an oxidizer from the external atmosphere.

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Appendices

IR – infrared.
PIV – particle image velocimetry.
PLIF – planar laser-induced fluorescence.
ABB – absolutely black body.

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