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Processing of thermogram sequences to determine the rotation rate of a vortex flame

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ABSTRACT

We study vortex flame radiation in laboratory conditions. A fire torch was burning from a tank, which was fixed at the axis of uprising swirl airflow. Ethanol was used as a fuel. Processing of a sequence of thermograms of a swirling torch is described. The vortex flame revolutions were calculated using FFT of time pulsations of a signal from a thermal imaging system.

1. Introduction

Fire whirls (FW) occur sometimes during large-scale natural and technogenic fires. They are characterized by stovepipe elongation of swirling fire fed by the fire source, both its part and as a whole. The impact of a FW on the environment strongly increases as a high-power surface air radial inflow into the FW base. Real-time studies of FW are expensive and dangerous; therefore, mathematical and physical simulations of this phenomenon are used.

Today, there are many works describing the phenomenon referred to, e.g., [1,2]; works devoted to the numerical simulation of FW [3], as well as works on the physical simulation of FW [4–6]. We should note work [7], where main researches of fire tornados are review. However, as far as we know, no studies were carried out on the use of thermal imaging for measurements of the flame rotation rate.

The setup for physical simulation of FW by means of a fire torch formed during ethanol burning in a tank fixed on the axis of uprising swirl airflow was described in detail in [8]. Applicability of a thermal imaging camera to measurements of the revolution per second (RPS) of the torch was briefly mentioned in [9]. This work is devoted to the detail description of experiments on the thermal imaging technique for measurements of RPS of torch. The urgency of this study is caused by opening prospects in remote measurements of RPS of different natural and technogenic FWs.

2. IR camera applicability

Maximal temperatures T of the fire torch during the experiments were 1000–1300 K. According to [10], the wavelengths of the radiation spectral power peak for an absolutely black body (Bb) are calculated by the equation

$$\lambda_{max}T = 3668\ \mu\text{m K}. \quad (1)$$

Hence, λ_{max} falls within the 2.8–3.7 μm range in this case. Most thermal imaging cameras (TIC) operate in this mid-IR region, in particular, a JADE J530SB camera (Cedip). A high emissivity factor ($\varepsilon \approx 0.8$) of fire from forest fuel materials was attained in experiments with this camera [11]. The ethanol spectrum in the range under study is similar to the spectrum of forest fuel materials [12]. Let us note that the level of energy emitted is lower by 2–3 orders of magnitude, which indicates mainly thermal imaging of the torch as compared to video recording.

The power F (W) of radiation in the spectral band $\Delta\lambda$ from the surface S of a radiator with a temperature T is defined as [13]:

$$F = \int_{\Delta\lambda} \varepsilon(\lambda)[dR(\lambda,T)/d\lambda]S d\lambda. \quad (2)$$

Here $R(\lambda, T)$ is the spectral radiant intensity of Bb (W/m^3), which is described by the Planck law:

$$R(\lambda,T) = 2\pi hc^2\lambda^{-5}(e^{\frac{hc}{kT\lambda}} - 1)^{-1}, \quad (3)$$

where h is the Planck constant; k is the Boltzmann constant; c is the speed of light.

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In addition to the Planck component and the emissivity factor ε (λ), which is a function of the radiation spectrum of gaseous components and soot particle concentration, the intensity of camera signals is affected by attenuation along the optical path and side-radiation sources.

In our laboratory experiment, the path was about 5 m long; therefore, no additional correction of the emissivity factor was carried out. Ambient light sources were absent. Let us estimate the ratio of the background ($T_1 \approx 300$ K) to fire ($T_2 \approx 1000$ K) signals. According to the Stefan–Boltzmann law,

$$\frac{F_{1000}}{F_{300}} = \frac{\sigma\varepsilon_r T_2^4}{\sigma\varepsilon_b T_1^4} = \frac{\sigma\varepsilon_r (1000)^4}{\sigma\varepsilon_b (300)^4} \approx 123.5, \quad (4)$$

where σ is the Stefan–Boltzmann constant; ε_r and ε_b are the emissivity factors of radiation source and background, respectively.

A thermogram is a torch projection. Flame is partly transparent [14]; therefore, the high-intensity region of any burning volume is shown as brighter area.

3. Experiment

The purpose of the experiment was to find RPS of the torch from a sequence of thermograms.

The diagram of the thermal imaging setup is shown in Fig. 1.

The JADE J530SB camera was equipped with an optical filter for operation in the 2.5–2.7 μm band. The image sensor is an array of 320 × 240 elements. To increase the spatial resolution, the camera was turned by 90° on the side; then the vertically elongated image of the torch was displayed along the long side of the receiving matrix. Distance to the camera was 5 m; the field of view of the camera was ~1 × 1.3 m. Two thermogram frame rates were used: 50 and 170 Hz.

Five thermocouples vertically spaced at 11 cm so as their working junctions were arranged along the vertical axis of the torch, beginning from 3 cm from the fuel surface, were used as temperature reference. The entire combustion process of a portion of fuel (20 ml of ethanol in the beginning of each test run in a thin-walled steel tank with a diameter of 142 mm and a side height of 10 mm) was recorded (~1 min). The electric motor was switched on immediately after the fuel ignition, which stipulated the presence of a transient stage. Fig. 2 shows the torch height in steady state visually estimated in the fire whirl model (FWM) as a function of the swirler frequency *n* (impeller with eight flat vanes; the inner/outer diameters are 180/320 mm; the angle of attack is 20°). Total of six firings were recorded (Table 1).

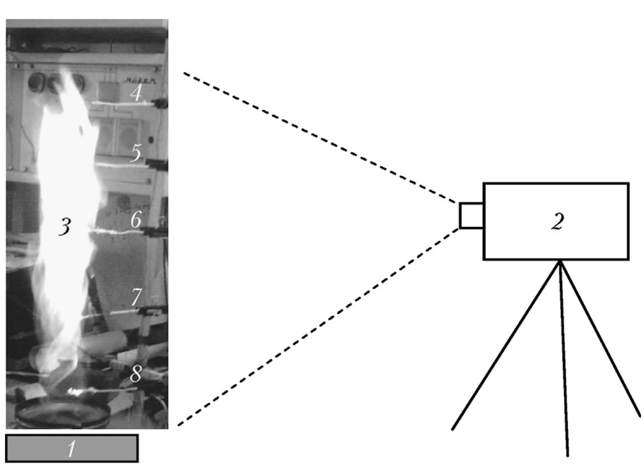

Fig. 1. Electric motor with impeller (*1*); IR camera (*2*); swirling torch flame (*3*); tree of reference thermocouples (*4–8*).

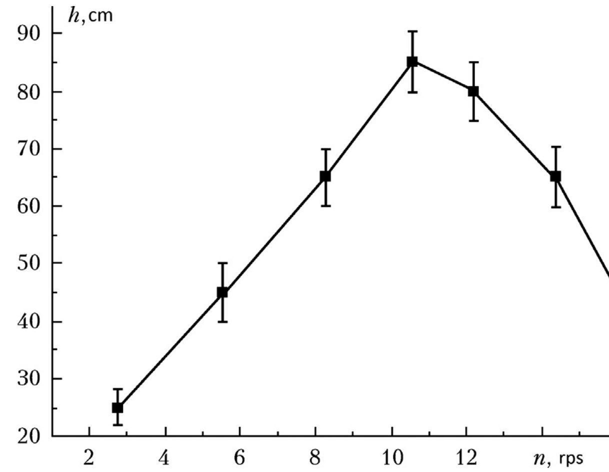

Fig. 2. Torch height.

4. Analysis of results

Fig. 3 shows a thermogram of the torch in steady state in test run no. 5. The scale shows the spectral brightness in digital levels (DL). When using this scale, the signals from fire are linearly proportional to the radiation energy received. Four bottom frames are shown by vertically equispaced high-intensity spots. To detect the stable combustion mode, torch cross-sections *1* and *2* were constructed in the thermograms at heights of ~10 and ~20 cm from the fuel tank. The height of upper cross-section *2* was selected so as the mean intensity in this cross-section did not exceed the corresponding value in lower cross-section *1*. In the opposite case, we recorded origination of whirling fire (FWM). Then the time curves of the mean intensities in those cross-sections were analyzed. Such a time sequence for firing no. 5 is presented in Fig. 4, where the thermogram number *N* is plotted along the horizontal axis and DL, along the vertical axis.

The interval of steady-state combustion was determined for each realization; the corresponding sequence of thermograms was used for calculation of Fourier spectra. The duration of the stable combustion mode decreases as the swirling frequency of the flame increases in realization nos. 1–5; the duration is minimal in realization no. 5. A further increase in swirling frequency (realization no. 6) increases the duration of the stable combustion mode and widens and shortens the torch (see Fig. 2).

We carried out a numerical experiment to determine RPS of the torch. A region of several pixels was discriminated on a thermogram. Then this region was projected on the sequence of thermograms of the stable combustions mode using special software. After that, time sequences were calculated on the basis of the mean, maximal, and minimal camera signals in that region for the following Fourier transform. It turned out that the best result, i.e., the peak amplitude of the maximum, that corresponded to the swirler frequency in the Fourier spectrum, was attained when the region consisted of the only one pixel in the near-axial region of the torch.

The thermogram peculiarity in the form of a peak in the flame swirling frequency disappears as the number of pixels increases. It was difficult to analyze the presence of other valuable frequencies, in addition to the frequency of the main peak; therefore, the spectra were analyzed using averaging. The averaging over 20 values turned out optimal in our experimental conditions, where the main peaks still remained and background peaks were suppressed (Fig. 5).