

Justification of choice of the spectral range for the study of combustion processes with the use of thermography in the middle IR range

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Abstract

The paper presents the emission spectra of flame formed during combustion of different fuels and gives the grounds for application of various narrow spectral ranges in the mid-infrared region to record the temperature fields in flame and flame screened objects.

Keywords: temperature, flame, IR radiation, thermal imager.

1. Introduction

As in the norm, a significant amount of thermocouples are used to determine the temperature flame fields in experimental studies of the combustion processes. At the same, there is a need to sacrifice "the purity of the experiment" because thermocouples perturb the medium under study, provide heat rejection from the chemical reaction zone through free ends and are have an inertia that can significantly exceeds the speed of processes. Up-to-date methods of thermography allow us to refuse the use of a significant amount of thermocouples and obtain a good spatial resolution in time.

However, the use of thermography is connected with a number of difficulties caused by the need to determine optical characteristics of flame (emission and transmission coefficients) [1, 2], the spectral range, and the effect of a flame layer on recording of screened objects [1]. For example, in the study of plant fuel combustion in the wavelength range of 2.5-2.7 microns it is observed the dependence of the emission coefficient of flame on the moisture content of fuels [2].

In the world, the thermography methods are mainly used for electrical and thermal equipment, which is connected with temperature measurements of solids, and often even with a qualitative evaluation of a temperature gradient. Thermography is also used to estimate behavior of microelectronic devices [3] and in problems of nondestructive control of loaded structures in aeronautical engineering [4]. The work [5] provides the emission spectra of flame formed during combustion of plant fuels and the results of radiation studies from the fire front for the wavelengths of 3.6, 4.8, 4.2 microns, and the work [6] provides the emission spectra and infrared measurements for various gases, including vapors of water and carbon dioxide heated up to 2000 K.

The works [7-9] provide the experimental results describing the emission properties of flame formed during combustion of forest fuels and the absorption ability of forest fuels. It should be noted that in these works the results are given for the near-infrared region and the initial part of the mid-infrared region, where there are powerful emission bands of combustion products. The work [10] provides the emission spectrum of flame formed during combustion of alcohol in simulation mode of fire tornado in the mid-infrared region. It should be noted that there is a forced influx of oxidizer and external flow stabilization in this mode of combustion, which certainly influences on the measurement results.

It should be noted that the medium-wave thermal imagers currently allow us to operate in the spectral range of 1.5-5.5 microns. In this spectral range there are the powerful gas emission bands formed during combustion of fuels. This paper

presents the experimental results for spectral characteristics of flame in the mid-infrared region, which is formed during combustion of different fuels and provides recommendations for selection of various spectral ranges to solve practical problems using the methods of IR diagnostics.

2. Experiment.

The following fuels were used: plant fuels (pine needles, cedar, and field plants), pine, birch, cedar, hardcoal (DO), alcohol, kerosene, petroleum, diesel fuel, and propane-butane mixtures. The mass of the plant fuel samples (cedar needles, pine needles, field plants) was 50 g, the mass of pine, birch and cedar was 200 g, the mass of hardcoal was 300 g, the volume of liquid was 20 ml.

The experimental setup includes the spectrograph (SOLAR TII MS2001i), the blackbody radiator (45/100/1100, Omsk plant OAO SPE "Etalon") that is considered to be a blackbody model (BB) and is used to obtain the reference spectrum of a blackbody at the maximum temperature of flame.

The emission spectrum of flame was recorded by the spectrograph (SOLAR TII MS2001i) with a measuring range of 2-5.3 microns. The number of photoreceiving elements was 384 with the step of 25 microns. The recording time of the spectrum was $2 \cdot 10^{-4}$ s. The maximum error in determining the wavelength was ± 0.78 nm; the average noise level for the scale DL (Digital Level) was 0.9 mV, the maximum was 4.2 mV. The speed of IR photoreceiving line was $2 \cdot 10^4$ s without averaging, the maximum sweep rate of the spectrum was 10.000 steps/sec. The measurements were conducted at a distance of 1 m from the flame. The temperature of flame was controlled by a type CA thermocouple with a junction diameter of 500 microns. The time constant of the thermocouple was equal to $\tau=10$ s, which allowed us to average the temperature flame fluctuations that existed during combustion of plant fuels with the frequencies of 2-7 Hz [2]. The Temperature measurement error in flame did not exceed 10%. In accordance with the maximum values of the thermocouple in flame, the emission spectrum of a blackbody model (BB) was recorded with the appropriate temperature at the same distance of 1 m. The blackbody radiator (45/100/1100, Omsk plant OAO SPE "Etalon") was used as a blackbody model with a range of temperature changes from 573 K to 1373 K.

At the initial stage of the experiment it was conducted the ignition of fuels that were packed with a natural packing density (for solid fuels) or were poured into a cylindrical container with a diameter of 0.15 m (for liquid fuels). Combustion of the propane-butane mixture was initiated by the domestic burner. After reaching a stable mode of combustion, it was performed, at least, three recordings of the flame emission spectrum and the maximum flame temperature was recorded. After that the emission spectrum of the blackbody model was recorded with a temperature equal to the maximum temperature of flame. The general scheme of the experiment is shown in Fig. 1.

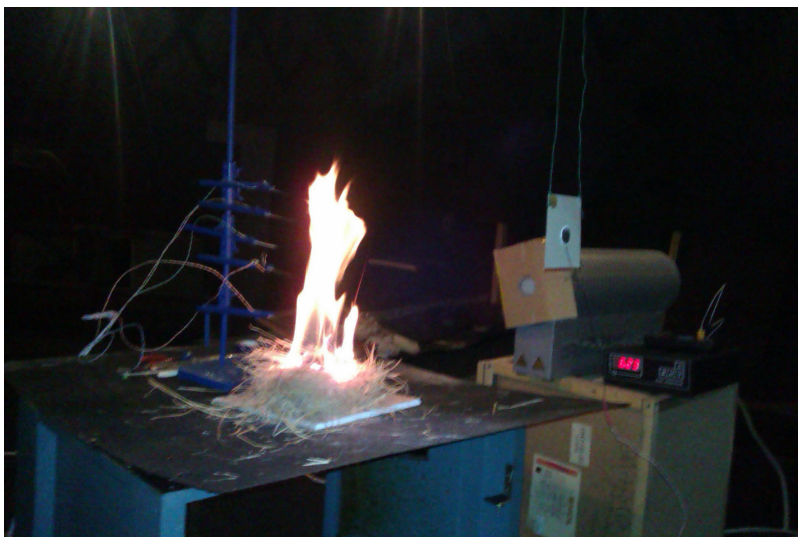


Fig. 1 Experimental setup.

Figs. 2-5 show the time-averaged recordings of the flame emission spectra (curve 2) formed during combustion of fuels mentioned above and the blackbody emission spectrum (curve 1) at a temperature corresponding to the maximum temperature of flame during combustion of fuels. These spectra were obtained for the same conditions and scales of the experiments.

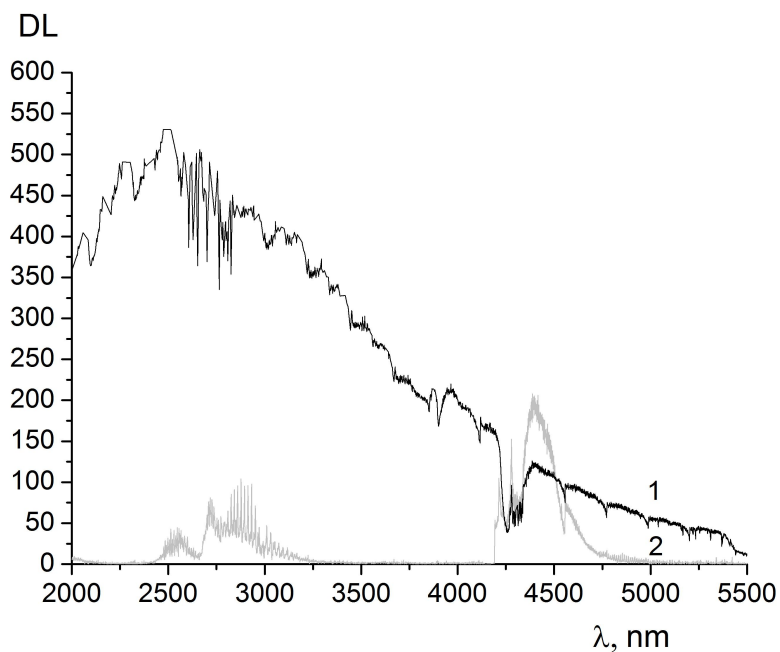


Fig. 2 Spectrum of blackbody emission (curve 1) and flame (curve 2) formed during combustion of the propane-butane mixture.

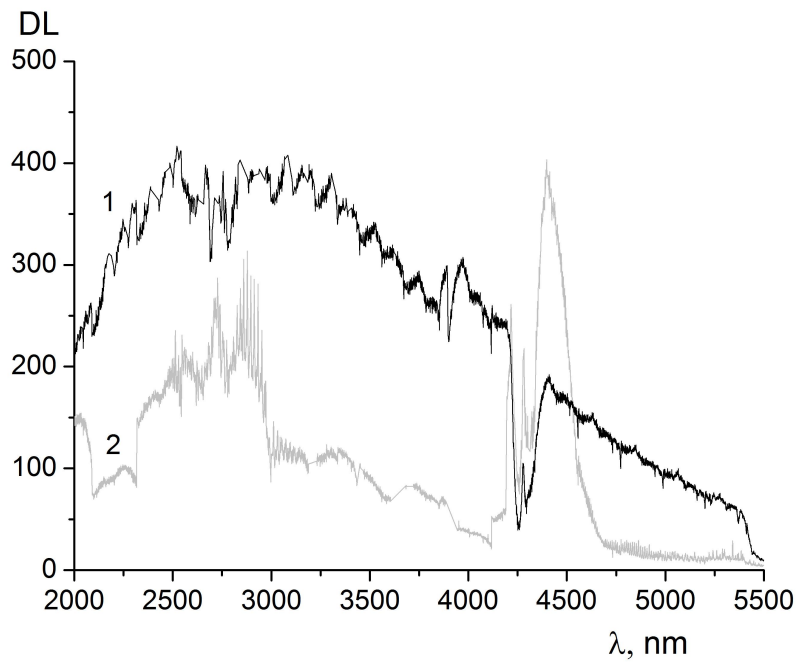


Fig. 3 Spectrum of blackbody emission (curve 1) and flame (curve 2) formed during combustion of petroleum.

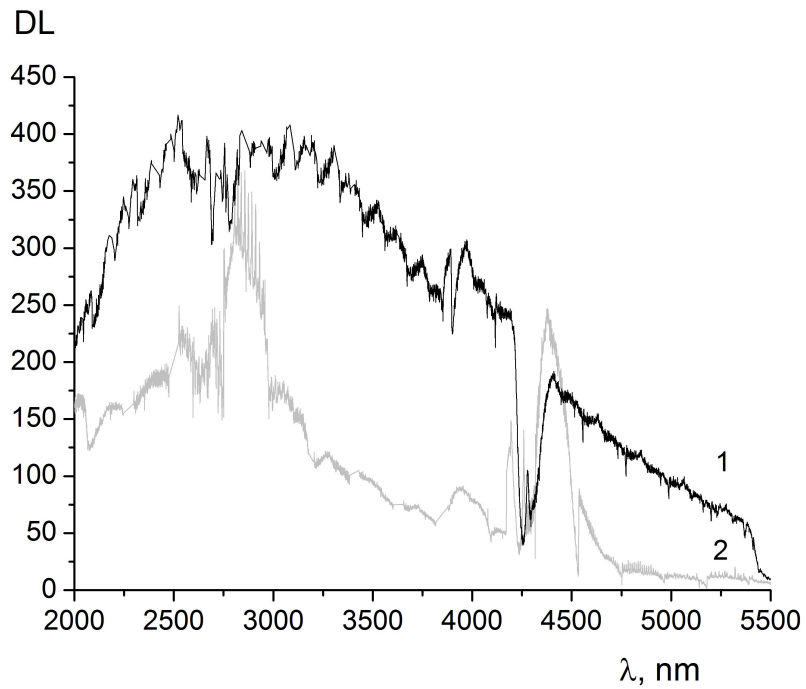


Fig. 4 Spectrum of blackbody emission (curve 1) and flame (curve 2) formed during combustion of kerosene.

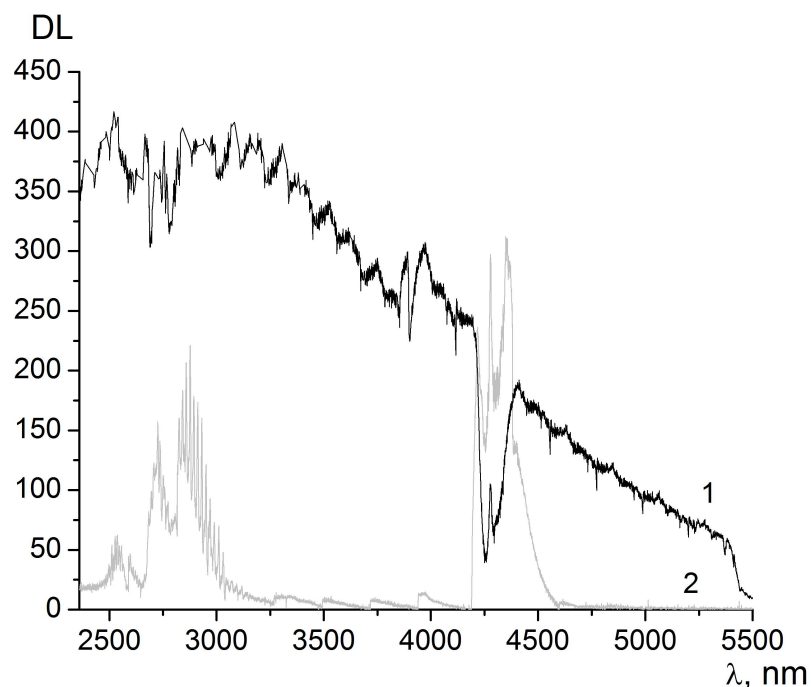


Fig. 5 Spectrum of blackbody emission (curve 1) and flame (curve 2) formed during combustion of alcohol.

Analyzing Figs. 2-5 and the composition of the combustion products under study, we can conclude that the most powerful emission lines correspond to vapors of water and carbon dioxide formed during combustion. This is clearly observed in the emission spectra for the propane-butane mixture and alcohol. Different intensity emission takes place in the flame emission spectrum during combustion of other fuels in the wavelength range of 2-4 microns. This emission is mostly caused by emission of the condensed combustion products (soot and smoke). It should be noted that the condensed combustion products emit almost like a blackbody, but the intensity of emission is connected with a concentration and, therefore, it is significantly lower than the emission intensity of gaseous combustion products emitting in the narrow spectral range.

It should be noted that during combustion of plant fuels under study, in the flame emission spectrum at the initial part of the spectral range there are the emission bands that are qualitatively similar to the emission spectra of flame in the range of 2.0-2.5 microns, given in the works [7 -9]. The flame emission spectrum formed during combustion of alcohol in Fig. 5 is almost identical to the spectrum presented in [10] and obtained using similar measuring equipment, but there is a difference in the amplitude of the measured signal. This difference was due to different modes of fuel combustion, which kept different influxes of oxidizer into the combustion zone.

In view of the fact that thermal imagers are calibrated by blackbody emission, and comparing the flame emission spectrum and the blackbody emission spectrum for the same maximum temperature, it can be seen that there is emission exceeding the intensity of blackbody emission in the range from 4 to 5 microns in the flame emission spectrum. It is obvious that selection of a narrow spectral region in the range of 4.0-4.7 mm is not appropriate to measure the flame temperature, since in this case it is necessary to take into account the concentration of the CO and CO₂ combustion products and their contribution to the integral flame emission, which is a rather complicated task.

To record the temperature fields in flame, the narrow spectral regions existing in the wavelength range of 2.5-3.0 microns are most preferred, because in this range the flame emission intensity does not exceed the intensity of blackbody emission for the corresponding temperature, and in this spectral range there are the powerful emission bands with an effective emission coefficient close to 1. For example, the spectral range of 2.5-2.7 microns is very convenient for vapor emission of water and carbon dioxide formed during combustion.

If the task is to record flame screened objects without recording of the flame temperature, then the narrow spectral range should be selected in the wavelength range of 3.3-4.0 micrometers, where there are no powerful absorption and emission bands of combustion products and there is only emission of condensed combustion products with a relatively low intensity. To obtain true power characteristics of the flame screened objects, there is a need to use the relation (1) given in [1], taking into account the transmission coefficient received for the spectral range used.

3. Conclusions

Based on the foregoing information, the following conclusions can be made:

1. To solve the problem of determining the temperature fields in flame, it is necessary to use narrow-band filters which transmit the emission bands of combustion products with an intensity that does not exceed the intensity of blackbody emission for the maximum flame temperature.
2. The spectral range of 2.5-3.0 microns should be used for determination of temperature fields in flame for the fuels considered in this paper.
3. The spectral range of 3.3-4.0 microns should be used for recording of objects screened by flame formed during combustion of the fuels considered in this paper. When using the spectral range of 2.5-3.0 microns for recording of emission of a flame screened object, in the integral value of recorded emission, the flame emission will make a significant contribution, which should be taken into account when calculating the true values.
4. The spectral range of 4.0-4.7 microns should not be used for measurement of the temperature and, in the general case, requires consideration of CO and CO₂ concentrations in combustion products.

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REFERENCES

- [1] Loboda E.L., Reyno V.V., Vavilov V.P. The Use of Infrared Thermography to Study the Optical Characteristics of Flames from Burning Vegetation // *Infrared Physics and Technology* 67 (2014). P. 566-573.
- [2] Loboda E.L., Reyno V.V. Influence of the emission coefficient of flame on temperature measurements by IR techniques during combustion of forest and steppe fuels with different moisture contents. Frequency analysis of temperature changes // *Atmospheric and Ocean Optics*. 2011. No. 11. Pp. 1002-1004.
- [3] W. Huang, K. Skadron, S. Gurumurthi, R.J. Ribando, M.R. Stan Differentiating the Roles of IR Measurement and Simulation for Power and Temperature-Aware Design Performance Analysis of Systems and Software, 2009. ISPASS 2009. IEEE International Symposium Digital Object Identifier: 10.1109/ISPASS.2009.4919624 Publication Year: 2009.
- [4] Vavilov V.P. Infrared thermography and thermal control. Moscow, "Spectrum" Publisher, 2009. 544 p.
- [5] J. Meléndez, J. M. Aranda, A. J. de Castro, F. López Measurement of forest fire parameters with multi-spectral imaging in the medium infrared // *Quantitative InfraRed Thermography Journal* Vol. 3, Issue 2, 2006. PP. 183-199.
- [6] W.T. Rawlins, W.G. Lawrence, W.J. Marinelli, M.G. Allen Hyperspectral infrared imaging of flames using a spectrally scanning fabry-perot filter // 2nd Joint Meeting of the U.S. Sections of the Combustion Institute. March 2001. Pp. 1-13.
- [7] Z. Acem, G. Parent, B. Monod, G. Jeandel, P. Boulet Experimental study in the infrared of the radiative properties of pine needles // *Experimental Thermal and Fluid Science*, 34 (2010). Pp. 893-899.

- [8] A. Agueda, E. Pastor, Y. Perez, E. Planas Experimental study of the emissivity of flames resulting from the combustion of forest fuels // *International Journal of Thermal Science*, 49 (2010). Pp. 543-554.
- [9] P. Boulet, G. Parent, Z. Acem, A. Collin, O. Sero-Guillaume On the emission of radiation by flames and corresponding absorption by vegetation in forest fires // *Fire Safety Journal*, Vol. 46, Issues 1-2, 2011. Pp. 21-26.
- [10] Sherstobitov M.V., Tsvyk P.Sh. Difference in the emission IR spectra of ethanol during free diffusion combustion under the air flow in modeling of fire tornado // *Russian Physics Journal*. 2013. V. 56. No 1. Pp. 90-94.