Application of thermography in experimental studies of plasma jets

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Abstract

The paper presents the experimental studies of the optical properties for the plasma jet in the mid-IR range.

Keywords: plasma, temperature, IR emission, thermography.

1. Introduction

Contact methods of temperature measurements are commonly used in experimental studies of combustion processes and the impact of plasma jets on various materials. In particular, thermocouples are used in experiments. The number of thermocouples increases significantly if there is a need to obtain a spatial temperature distribution. This is connected with certain difficulties, including technical problems.

For example, in the study of temperature distribution in flame the use of thermocouple rakes can not provide good spatial resolution, in addition, thermocouples perturb the medium under study, their free ends are used for heat sink, emission of thermocouples can also change the state of the medium. Measuring the surface temperature of material subjected to the plasma jet is connected with technical difficulties when there is a need to embed a thermocouple in the surface of the material subjected to destructive impact of the plasma jet. High frequency pulse has an impact on the recording equipment during the start of plasma jets through free ends of thermocouples, which does not allow ADC and precision measuring instruments to be used. Up-to-date methods of thermography using thermal imagers allow us to refuse the use of a large amount of thermocouples and avoid the difficulties described. At the same time, application of infrared thermography provides a significantly higher resolution in space and time.

However, the application of these methods causes difficulties connected with determining the coefficients of emission and transmission of the medium under study, selecting the spectral range of studies, the effect of high-temperature translucent medium (flame, plasma jet) on the recording of temperatures from screened objects. For example, in the study of plant fuels in the spectral range of 2.5-2.7 microns, the emission coefficient of flame is dependent on the moisture content of fuels [1].

A lot of investigations in the field of thermography for electrical and thermal equipment are connected with measurements of temperatures in solids. Thermography is widely used to study the behavior of microelectronic devices [2] and in problems concerning nondestructive control of honeycomb structures in aeronautical engineering [3]. To determine the temperature profile in the front of exothermic autocatalytic reactions, the methods of thermography were used in the work [4], in particular, the thermal imager FLIR SC 5500 was used with a spectral range of 2.5-5 microns.

However, the emission spectrum of the reaction front was not provided in the work, and for the combustion processes, the use of such a broad spectral range is incorrect, because all thermal imagers functionally are made to measure temperatures and are calibrated according to emission of a blackbody model (BB) and the emission spectrum is determined by the Planck's law. In the field of combustion processes and, in particular, wildland fires the thermography methods are not widely used due to the complexity of objects under study, the lack of knowledge of properties, such as the emission coefficient and high costs of special thermal imagers appropriate for scientific research.

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However, in view of prospects of this method for determining the characteristics of the combustion front we can emphasize the works [5-7], where the measurement of parameters for forest fires is conducted in the mid-infrared wavelength range, and the works [8, 9] provide the results of the study in the spectral ranges of 7.5 -13 microns and 8- 12 microns, respectively.

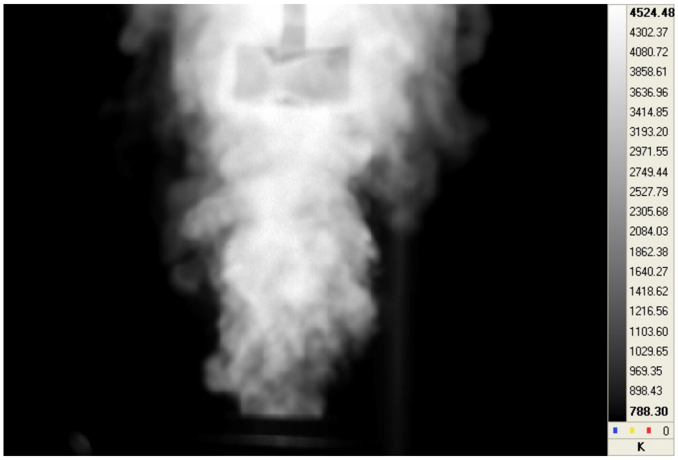
The work [10] provides the development of an electric-arc gas heater, where a mixture of air and water vapor is used as a working body. Taking into account that in the study of combustion processes, a spectral range with emission bands of water vapors is used to determine the temperature field in flame, the same approach is of interest to study the plasma jets produced from a mixture of air and water vapors. This paper presents the experimental results for optical properties of the plasma jet obtained by the electric-arc gas heater EDP-104A/50, where air, nitrogen, carbon dioxide and argon were used as the working bodies.

2. Experiment and results

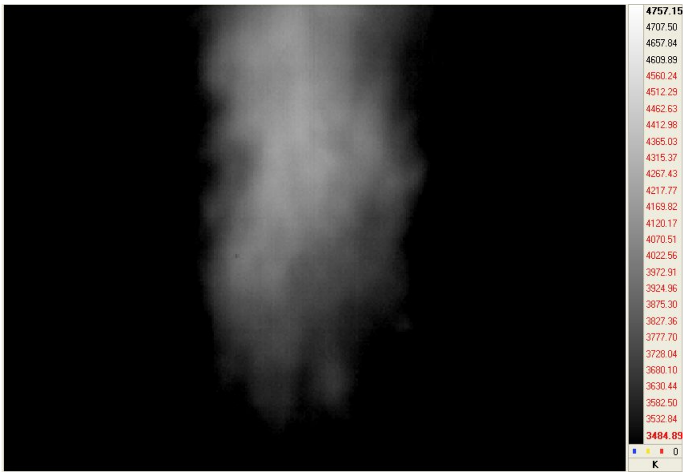
The plasma jet was generated using the electric-arc gas heater EDP-104A/50 developed at the Institute of Thermal Physics SB RAS, which allowed us to obtain a plasma jet at a rate up to 60 m/s. Swirling of the flow was conducted by a swirling ring that was a part of the EDP-104A/50, and the additional gas-vortex stabilization of the arc was conducted by using the stepped anode with an outlet diameter of 14 mm. Air, nitrogen, and carbon dioxide were used as the working bodies. The maximum temperature of a jet was 4500 K for carbon dioxide, 5500 K for air and nitrogen and 8000 K for argon.

Infrared emission and temperature distribution were recorded by the thermal imager JADE J530SB with narrow-band filters and with the spectral intervals: 2.5-2.7 microns, 2.64-3.25 microns, 3.1-3.3 microns, 3.7-3.9 microns, 4.0-5.0 microns, 4.35 microns with a transmission band of 180 nm, and 4.0-5.5 microns. Recording was conducted at a rate of 50 frames/sec and by a camera lens with a focal length of F = 100 mm and with the 320x240 pixels matrix of the thermal imager. The distance from the thermal imager to blackbody was 2.5 m, and the distance from the thermal imager to the axis of the plasma jet was 2 m.

The sample of a thermal protection material with an emission coefficient ε=0.9 was placed in the plasma jet. To determine the transparency of the plasma jet, a model of blackbody was located on the optical axis "thermal imager-plasma jet". The blackbody radiator (45/100/1100, Omsk plant OAO SPE "Etalon") with the range of temperature changes from 573 K to 1373 K was used as a blackbody model. The temperature of blackbody was 1373 K. Fig. 1 shows the thermograms of the plasma jet, where the working body is carbon dioxide. It is seen that details of the flow on the thermogram obtained for the 4.35 micron filter, where there is the emission band of carbon dioxide, is expressed better than for the filter with a considerably wider bandwidth of 2.5-2.7 microns.



a

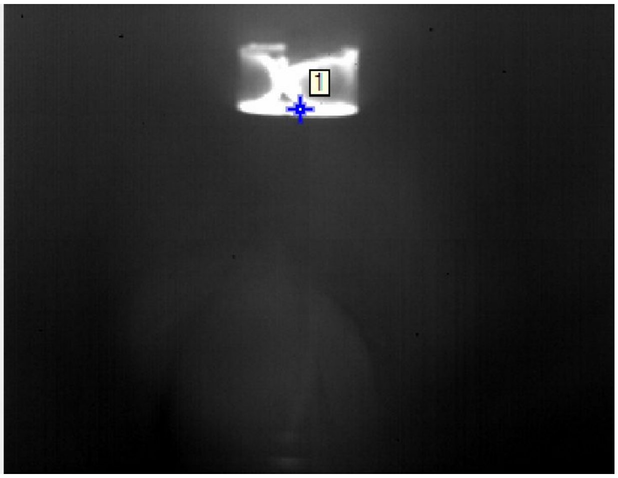


b.

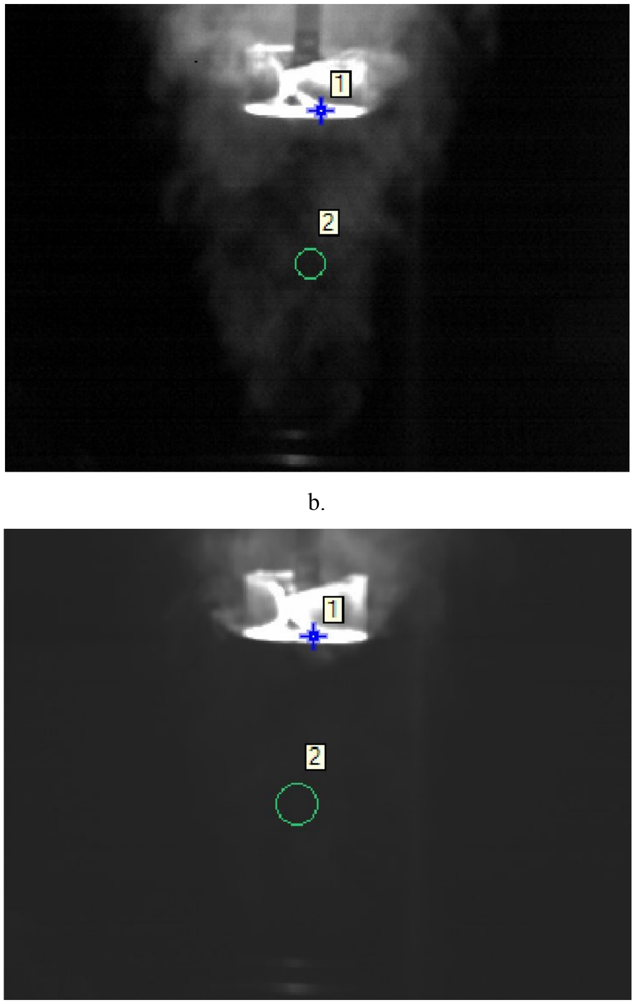
Fig. 1 Thermogram of the plasma jet obtained by using the 4.35 micron filter with a bandwidth of 180 nm and an integration time of 3 µs (a) and the filter with a bandwidth of 2.5-2.7 microns and an integration time of 820 µs (b).

Fig. 1a was obtained by using the 4.35 micron filter with a bandwidth of 180 nm, where there was a powerful emission band of carbon dioxide, and Fig. 1b was obtained by using the 2.5-2.7 micron filter. It is obvious that in the first case the higher selectivity of the filter and a significantly smaller integration time provide a good detailed image of the plasma jet with an effective emission coefficient close to 1. The averaged image with a low effective emission coefficient was obtained for the filter with a wider bandwidth and larger time of integration.

Fig. 2 shows a thermogram of the plasma jet obtained by using nitrogen, and Fig. 3 shows a thermogram of the plasma jet obtained by using air.



a.

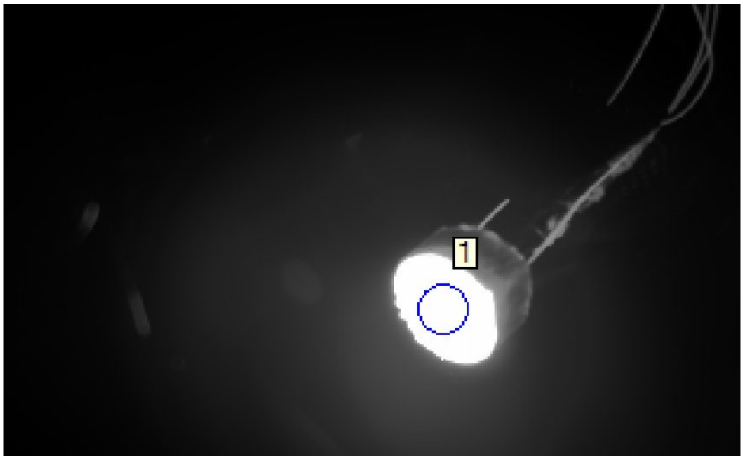


b.

c.

Fig. 2. Thermogram of the plasma jet (nitrogen) obtained by using a filter with a bandwidth of 2.5-2.7 microns (a), a filter with a bandwidth of 180 nm and the center of 4.35 microns (b), and a filter with a bandwidth of 4.0-5.0 microns (c).

a.



b.

Fig. 2. Thermogram of the plasma jet (air) obtained without the use of filters (a), and by using a filter with a bandwidth of 3.1-3.3 microns (b).

It should be noted that in the wavelength range of 3.7-3.9 microns there is no any emission of the plasma jet in air, nitrogen and carbon dioxide or it is significantly below than the sensitivity of the thermal imager, which allows this range to be efficiently used for the recording of objects subjected to the plasma jet and screening. When air and nitrogen were used as working bodies, there is emission of the plasma jet in the spectral range of 2.5-2.7 microns, 2.64-3.25 microns, 4.0-5.0 microns for the wavelength of 4.35 microns. It should be noted that the emission coefficient in these cases is less or equal to 0.1. Such the low emission coefficient results in a substantial reduction in the measurement accuracy.

For the thermal recording in the whole operating range of the thermal imager (2-5 microns), a powerful emission of the plasma jet leads to saturation of the matrix in the thermal imager, since the sample of the heat protection material has properties of a gray body with a high emission coefficient. By using carbon dioxide as a working body, there is emission of the plasma jet with a high intensity for the wavelength of 4.35 microns.

In this case the application of the 4.35 micron filter with a bandwidth of 180 nm leads to a good-quality detailed thermal image of the plasma jet. In addition, the correct calibration of the thermal imager allows us to measure the temperature fields with the emission coefficient equal to 1 and avoid the measurement error that occurs for the low emission coefficient.

3. Conclusions

1. The spectral range of 3.7-3.9 microns is recommended to be used for recording of objects screened by the plasma jet obtained in air, nitrogen and carbon dioxide.
2. The filter with a bandwidth of 180 nm and the center of 4.35 microns is recommended to obtain good detailed thermograms of the plasma jet obtained in carbon dioxide.

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