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NOVEL RADIO SYSTEMS AND ELEMENTS

Two-Color Pyrometry Methods for Measuring the Surface Temperature of Materials Exposed to a Plasma Jet

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Abstract—The choice of a radiation high-speed non-contact method for measuring the surface temperature of an object under the influence of a hydrogen plasma jet is substantiated. A theoretical assessment was made of the contribution of the intensity of recombination and bremsstrahlung plasma radiation to the pyrometer readings. It is shown that under certain conditions hydrogen plasma can be considered transparent to the thermal radiation of the material in the mid-IR wavelength (MWIR) range of 3–5 μm. An infrared spectral ratio pyrometer based on an uncooled two-spectral MIR photodiode with a sandwich structure, designed to control the temperature of an object under study in an experimental setup of a hydrogen plasma gun, is considered. The experimental results of monitoring the surface temperature of some composite material samples in the process of pulsed plasma exposure are presented.

Keywords: spectral ratio pyrometer, two-spectral MIR photodiode sandwich, composite materials, hydrogen plasma, plasma–wall interaction

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INTRODUCTION

Fundamental and applied research aimed at studying the interaction of plasma with matter is currently being actively carried out [1, 2]. In this kind of research, ultra-high thermal loads (up to hundreds of GW/m^2), which, purposefully or forcedly, lead to a change in its physical (thermal, mechanical, optical) properties. Qualitative and quantitative assessment of these properties can be carried out by monitoring the dynamics of sample temperature change both during the impact of a powerful thermal pulse (sample heating) and after its completion (sample cooling) [3]. The features of pulsed plasma heating include a short-term large thermal-mechanical pulse transmitted to the sample [4], which is capable of destroying the surface layer, and a complex process of heat exchange between the plasma and the sample, in which a near-wall plasma is formed, with chemical reactions occurring in it. These features give rise to the main problems associated with temperature measurement: high rates of thermal processes in a thin layer of the sample, structural changes that occur that affect the emissivity of the surface, and intense near-wall plasma radiation in the visible range [5]. Under such conditions, it is possible to use only non-contact methods for measuring temperature, namely, the method of two-color pyrometry outside the visible radiation range. In this method, the temperature is calculated from the ratio of the recorded powers of the object's thermal radiation on two closely spaced spectral lines in the mid-IR region. This makes it possible to eliminate the effect of the emissivity of the sample of the material under study (ε), which in most cases is unknown and changes with a high probability during plasma heating. In addition, unlike other radiation methods for measuring temperature, the two-color method is not sensitive to changes in the shape and area of the measured surface, as well as the possible attenuation of radiation in the intermediate medium (gas contamination, dusting of protective glasses, etc.) [6].

1. DESCRIPTION OF THE EXPERIMENT

Figure 1 shows a photograph of the experimental setup, a stand for a hydrogen plasma gun with a pyrometric sensor to control the temperature of a sample of the material under study. An experiment to study the effect of plasma on various materials proceeds as follows: a coaxial accelerator generates a hydrogen plasma pulse with a duration of ~10–15 μs, particle density up to 10^{15} cm^{-3}, and kinetic energy of protons up to 300 eV. The jet power density reached 100 GW/m^2 [7], which collides with the sample located in the cross (marked with number *3* in Fig. 1);

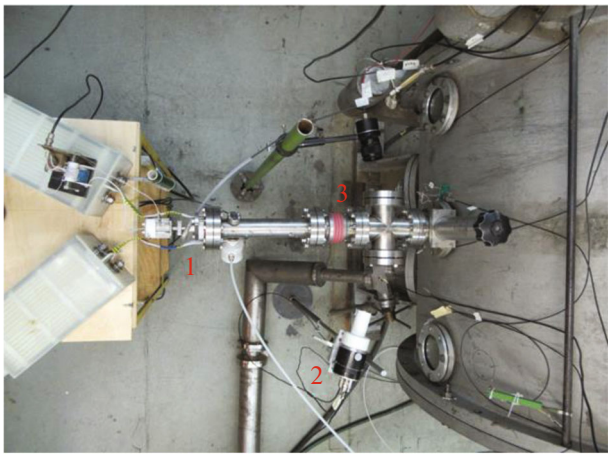

Fig. 1. Photo of the experimental setup: coaxial accelerator (*1*), pyrometer (*2*), the location of the test sample (*3*).

a pyrometer directed at the sample surface registers radiation in two spectral channels lying in the mid-IR region.

2. THEORETICAL SUBSTANTIATION OF THE CHOICE OF THE SPECTRAL RANGE OF TEMPERATURE MEASUREMENT

One of the main factors limiting the possibilities of radiation methods for measuring the temperature of samples is the intense recombination radiation and radiation of the near-wall plasma, which occurs when the plasma jet decelerates upon collision with a sample of the material under study. Bremsstrahlung arises as a result of scattering of ions and electrons in the electric field of the plasma.

Figure 2 shows the results of theoretical calculations [5] of the dependence of the power density of recombination and bremsstrahlung on the temperature of the hydrogen plasma jet near the sample wall (eV) for three different particle concentrations. The same graph shows the dependence of the specific power of the thermal radiation of an object in the region of 3 μm (under the condition $\varepsilon \approx 1$) on the surface temperature of the material. The choice of this wavelength is due to the decision to use photodetectors of the mid-IR wavelength (MWIR) range of the spectrum as a sensitive element of the pyrometer. The calculation is given for different concentrations of particles without taking into account impurities in the near-wall plasma.

It can be concluded from the graph that, under certain conditions (at a plasma temperature of more than 10 eV and a moderate concentration of particles), the near-wall plasma can be considered transparent to thermal radiation of the sample surface. Taking into account the absence of intense hydrogen emission lines in the region of 3–4 μm, the choice of the MWIR range of the spectrum for pyrometric measurements and the appropriate MIR-photodiode heterostructures developed at the Ioffe Institute can be used to solve the problem [8].

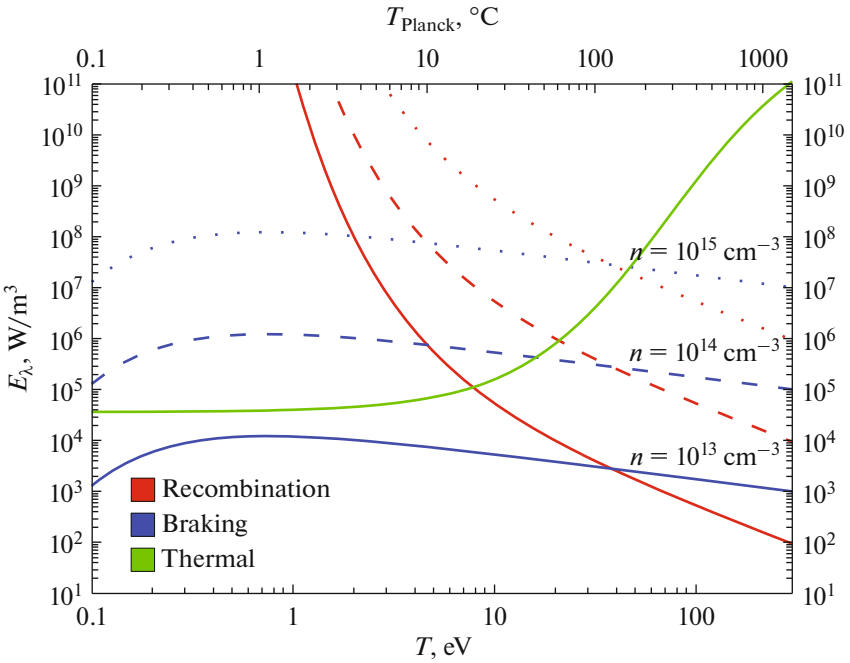

Fig. 2. Dependence of the power density of recombination, bremsstrahlung, and thermal radiation on the plasma and sample temperatures, respectively.

3. TWO-COLOR PYROMETRIC SENSOR: MAIN CHARACTERISTICS, CONVERSION FUNCTION (TEMPERATURE CALCULATION), AND CALIBRATION

The main element that determines all the measuring capabilities of pyrometers is the sensitive element. Especially for the problems of multispectral pyrometry, a dual photodiode (sandwich structure) was developed, which consists of two sequentially glued InSb and InAsSb heterostructures [8]. The first layer has a maximum sensitivity to radiation in the range of 3.0–3.4 μm, the second layer, in the range of 3.8–4.3 μm (in terms of the spectral sensitivity level, 0.5 from the maximum). Features of the manufacturing technology of the used photodiode structure, illumination from the substrate side (flip-chip configuration) and immersion coupling with a silicon lens (hemisphere with a diameter of 3 mm) provide not only an increase in the detecting ability of the photodetector due to an increase in its effective area while maintaining the level of intrinsic noise, but also suppression of radiation in the visible spectral region by at least 120 dB [9]. The latter is especially important for the use of pyrometers in experiments associated with the presence of strong illumination in the visible region of the spectrum.

Each layer of the sandwich structure, which is an independent photodetector, has its own electrical output. Thus, in the sensitive element, during detection, the spectral separation of radiation from the object into two channels occurs: channel 1 registers radiation in the spectral range $\Delta\lambda_1 = (3.2 \pm 0.2)$ μm, and channel 2, in the spectral range $\Delta\lambda_2 = (4.05 \pm 0.25)$ μm.

The currents recorded by the heterostructures are converted into measurable voltage signals by independent signal amplification/filtering circuits in the frequency band of 2 MHz, based on low-noise precision operational amplifiers (op-amps), whose characteristics are optimized to turn on mid-IR photodiodes with low dark resistance [10].

The sandwich structure chip, together with the dual amplifier op-amp chip, is placed in a sealed case on a Peltier thermoelement (TEP), which is an element of the case design, that is necessary for temperature stabilization of the characteristics of the dual photodiode and the op amp. The temperature of the sandwich structure and preamplifier/current converter circuits stabilizes at (20 ± 2)°C and supported with precision ±0.1°C thus ensuring minimum power consumption of the TEP. The stabilization temperature is controlled by a microprocessor.

On the basis of this photodiode, a two-color pyrometer was developed, the electronic part of which ensured the detection of thermal radiation and linear conversion into voltage signals over two spectral channels in the frequency band up to 2 MHz. Further, these signals were sent to the digitization and transmission unit for further computer processing. In our experiments, we used a 4-channel digital oscilloscope with a 12-bit ADC and a bandwidth of 100 MHz (ASK-3107 by Aktakom).

The optical scheme of the pyrometer is based on a zinc selenide focusing lens (focal length $f = 10$ cm, diameter $d = 2$ cm). In combination with a silicon lens mounted directly on a photodiode sandwich structure, this scheme provides temperature measurement in a 2-cm diameter of an object at a distance of up to 1.5 m (which corresponds to a sighting index of 1 : 75).

Taking into account the relative narrow-band spectral channels of the photodiode sandwich structure ($\Delta\lambda/\lambda \approx 0.1$) to establish a connection between the recording signal (photodiode current) and the temperature of object T it is possible to use a monochromatic expression for the spectral density of the recorded thermal radiation per unit surface area of an object in the form of Planck's law in the Wien approximation, which can be considered as the transfer function of the measuring channel of the pyrometer:

$$I(T) = I_0 + A\frac{C_1}{\lambda_{\text{eff}}^5}\exp\left(\frac{C_2}{\lambda_{\text{eff}}T}\right), \tag{1}$$

where I_0 is the dark current of the photodiode; A is the calibration coefficient, depending on the area of the object under study, its emissivity, ε, the transmission coefficient of the intermediate medium and parameters of its optical and electrical circuits; C_1 and C_2 are the Planck constants, $C_1 = 3.7415 \times 10^{-4}$ W μm^2, $C_2 = 14388$ μm K; and λ_{eff} is the effective wavelength corresponding to the maximum spectral sensitivity of the separate spectral measuring channel of the photodetector.

This approximation makes it possible to obtain a simple functional dependence for calculating the temperature from the ratio of useful signals from two independent outputs of a two-color pyrometer, which are sensitive in narrow spectral regions: 3 μm—$I(3)$ and 4 μm—$I(4)$:

$$T = C_2\left(\frac{1}{\lambda_{\text{eff}}(4)} - \frac{1}{\lambda_{\text{eff}}(3)}\right) \times \left(\ln\left(\frac{\lambda_{\text{eff}}^5(3)\,SR(3/4)}{\lambda_{\text{eff}}^5(4)\,K}\right)\right)^{-1} - 273, \tag{2}$$

where $SR(3/4) = (I(3) - I\text{o}(3))/(I(4) - I\text{o}(4))$ is the ratio of currents at the output of the photodiode sandwich structure, $\lambda_{\text{eff}}(3)$ and $\lambda_{\text{eff}}(4)$ are the effective wavelengths of the measuring channels of the pyrometer, and $K = A_1/A_2$ is the pyrometer coefficient, which depends only on the configuration of its optical and electrical circuits.

The pyrometer calibration was carried out on a sample of stainless steel and samples of composite materials with unknown values of emissivity: carbon composite material (CCM) and quartz composite

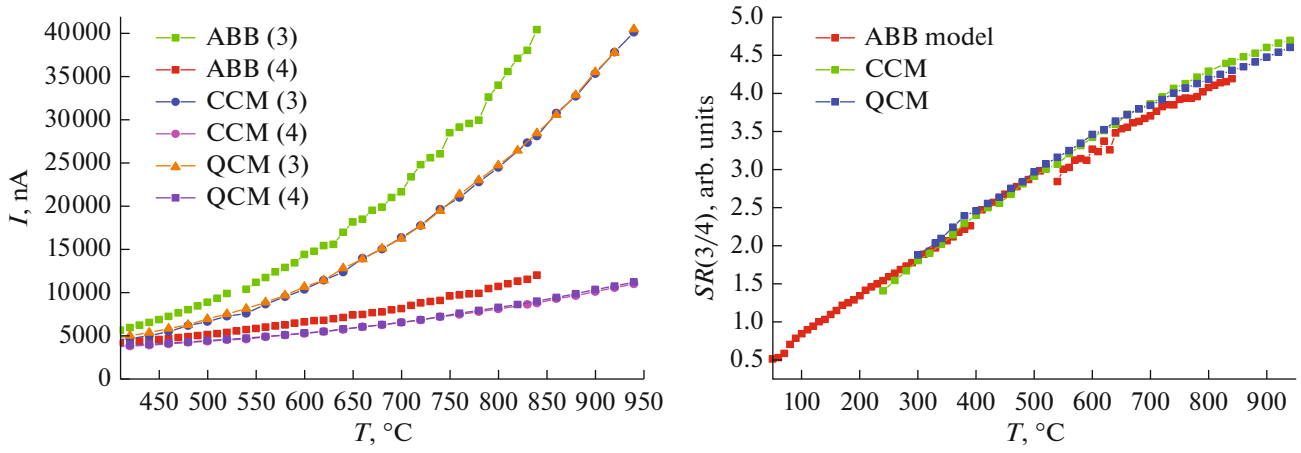

Fig. 3. Calibration dependencies for each of the spectral channels of the pyrometer (left) and for the ratio of the signals of two spectral channels (on the right), obtained for different materials.

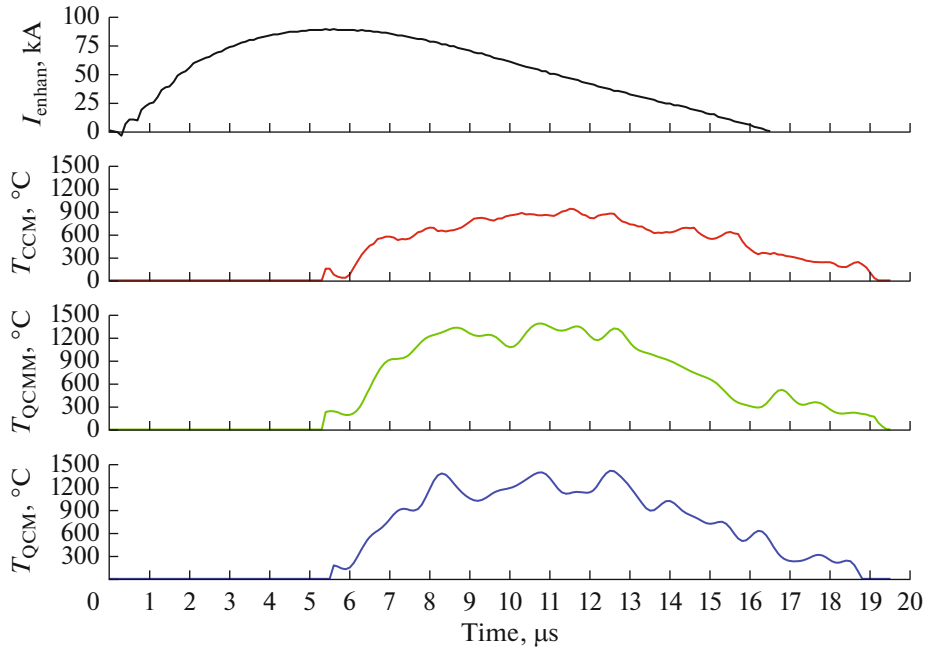

Fig. 4. Time dependence of the current signal on the accelerator and the dynamics of surface temperature changes of various composite materials.

material (QCM), which were then studied on a plasma setup. A material sample from unpolished annealed (at 1000°C) stainless steel was considered by us as a model of a blackbody (black body), since, according to [11], it potentially has the highest emissivity value ε among known materials in the temperature range up to 600°C with a smooth increase at higher temperature, specific for all metals. The samples were placed in a muffle furnace with a built-in thermocouple, where they were heated to 850–950°C. The temperature of the sample surface was recorded simultaneously using a reference chromel-alumel thermocouple and a pyrometer using channels of 3 μm and 4 μm. Next, the obtained data were approximated using expression (1) with the selection of effective wavelengths within the spectral sensitivity range of the photodiode, calibration coefficients, and dark currents for each of the measuring spectral channels. The calibration results are shown in Fig. 3.

As can be seen from Fig. 3, despite the significant difference in the magnitude of the signals for individual spectral channels obtained on a sample close in its characteristics to the blackbody model and samples with an unknown (lower) emissivity, the output signal

of a two-color pyrometer turns out to be the same. This is convincing evidence of the independence of the pyrometer signal from the characteristics of the material and, most importantly, allows its calibration and periodic verification on an arbitrary object in the laboratory.

The results made it possible to estimate the uncertainty of the temperature calculation experimentally using (2). According to five independent calibration series performed on different samples, the experimentally confirmed calculation error lies within ±1.5% relative to calculations using the Planck formula for temperatures up to 1200°C. This corresponds to the best sample of two-color pyrometers [12].

4. EXPERIMENTAL RESULTS: ANALYSIS AND PROSPECTS

The experiments were carried out on a varios samples of composite materials directly during exposure to a hydrogen plasma jet formed at a voltage of 5 kV on the capacitor storage of the plasma gun accelerator.

Figure 4 shows the time dependences of the current signals at the accelerator and the results of temperature calculation in accordance with expression (2) for a CCM, a QCM with a melted surface, and with a nonmelted surface.

It can be seen from a comparison of the data that there is a difference in the mechanisms of plasma interaction with samples of different composition and structure. The difference in the thermophysical properties of the quartz and carbon composite material can be judged from the different peak heating temperatures of the sample surface, which differ by ~200–300°C at the same voltage on the accelerator.

The interpretation of the results of measurements and calculations is complicated by the not fully understood physical processes of the interaction of hydrogen plasma with composite materials of different chemical composition and structure, as well as by the not fully understood properties of plasma itself.

CONCLUSIONS

It is shown that it is possible in principle to control the dynamics of changes in the surface temperature of various materials with a high time resolution (1 μs) in the process of pulsed plasma exposure. However, a large number of external influencing factors require additional experiments and the creation of an information-measuring model that takes into account the variety of physical processes in the interaction of plasma with the surface of materials in order to substantiate the reliability and accuracy of temperature measurements.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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