Control of dispersed-phase temperature in plasma flows by the spectral-brightness pyrometry method

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Abstract. In the present work, we propose a new method for measuring the distribution of temperature in the ensembles of condensed-phase particles in plasma spray flows. Inter-relation between the spectral temperature of the particles and the distribution of camera brightness signal is revealed. The established inter-relation enables an in-situ calibration of measuring instruments using the objects under study. The spectral-brightness pyrometry method was approbated on a Plazer plasma-arc wire spraying facility at the Paton Institute of Electrical Welding (Ukrainian Academy of Sciences, Kiev) and on the Thermoplasma 50-1 powder spraying facility at the Institute of Theoretical and Applied Mechanics (Russian Academy of Sciences, Siberian Branch, Novosibirsk). The work was supported by the Russian Foundation for Basic Research (Grants Nos. 14-08-90428 and 15-48-00100).

1. Introduction

Studies of multiphase plasma flows present a vital task due to the broad spectrum of relevant scientific and applied problems. Interaction of a dispersed phase with plasma is under study in such fields as combustion, jet propulsion, and high-temperature synthesis of materials [1, 2]. Control of heat- and mass-transfer processes of plasma with condensed particles is a key problem in the development of metal- and ceramic-coating spraying processes [3].

In diagnostics of multiphase plasma flows, the aggressive medium and the non-uniformity of the high-temperature flow leave no alternative to optical pyrometry methods [4]. However, using such methods is largely restricted by the short observation time of objects in the rapidly moving dispersed phase. The brightness pyrometry approach calls for its further development toward the control of moving objects. Spectral pyrometry methods have low temperature sensitivity, which circumstance strongly restricts the capabilities of those methods in constructing hyper-spectral images with a time constant of order 100 µs [5, 6]. Thus, new pyrometry methods need to be developed for solving the problem of measurement of the temperature of condensed-phase particles in plasma spray flows.

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2. **Principles of spectral-brightness pyrometry**

The basis for the spectral-brightness pyrometry (SBP) is the idea of *in-situ* calibration of imaging means to be performed through comparison of statistical characteristics of the distributions of digital monochrome camera signals and digital spectrometer signals registered while measuring one and the same ensemble of dispersed-phase particles. To this end, the camera measurement volume and the spectrometer measurement volume in the dusted plasma flow are to be made coincident (Fig. 1).

Powder materials intended for spraying coatings normally exhibit good uniformity of their optical properties. Providing that the spectral emissivity of the material in the working temperature range exhibits no sharp variations, then, for a narrow spectral region, one can use the grey-body approximation and assume the emissivity factor of dispersed-phase particles, or their coefficient of radiation, to be unknown constant $\varepsilon = \text{const}$. Then, under the condition that some reference thermodynamic temperature $T_s$ can be put in correspondence to each reference signal level $b_s$ of the brightness pyrometer, for an arbitrary signal level $b$ the temperature in the Wien region can be found by the formula

$$
T = \left(\frac{1}{T_s} + \frac{\lambda_b}{C_2 \ln \left(\frac{b_s}{b}\right)}\right)^{-1},
$$

(1)

where $\lambda_b$ is the wavelength of the brightness-pyrometer light filter, $\mu$m; and $C_2 = 14388 \mu$m·K [7].

We assume that, as the detector in the digital spectrometer, a charge-accumulating multi-element photo sensor is used. We denote the signal measured by the spectrometer and corrected for distortions in the electronic and optical paths of the instrument as $q(\lambda, T)$. During observation of an object with uniform temperature $T_s$, linearization of its optical emission spectrum plotted in the variables $x = C_2/\lambda$ and $y = \ln(q \cdot \lambda^4)$:

$$
y = -\frac{1}{T}x + \text{const}
$$

(2)
allows identification of the shape of the object and determination of its thermodynamic temperature from the slope of the plotted curve:

\[ T = -(dy/dx)^{-1}, \]  

(3)

Consider a digital image of the measurement volume of the camera and spectrometer. Let each image element be characterized by an arbitrary signal level \( b_k \), where \( k \) is the number of the element in the 2D photo sensor of the camera (here, linear indexation is used). Then, according to the radiation law of real bodies in the Wien approximation, some temperature \( T_k \) corresponds to this signal:

\[ b_k = A \cdot \varepsilon \cdot C_1 \cdot \exp \left( - \frac{C_2}{\lambda_b \cdot T_k} \right) = A_1 \cdot \exp \left( - \frac{x_b}{T_k} \right). \]  

(4)

In formula (4), \( A \) is the sensitivity of the digital camera; \( C_1 = 37418 \) W·μm\(^4\)/cm\(^2\); \( x_b = C_2 / \lambda_b \); and \( A_1 = \text{const} \) at fixed parameters of the camera measuring tract. The spectrometer integrates radiation coming from the entire projection of the measurement volume; hence, the integral signal of the spectrometer \( q_{\text{sum}} \) can be expressed in terms of temperatures that correspond to the respective image elements:

\[ q_{\text{sum}}(\lambda) = \sum_k q(\lambda, T_k) = B \cdot \varepsilon \cdot C_1 \cdot \sum_k \exp \left( - \frac{C_2}{\lambda \cdot T_k} \right) = B_1 \cdot \sum_k \exp \left( - \frac{x}{T_k} \right). \]  

(5)

In formula (5), \( B \) is the sensitivity of the spectrometer, and \( B_1 = \text{const} \) at all parameters of the spectrometer measuring tract being fixed. Following the passage to auxiliary coordinates (2), relation (5) assumes the form

\[ y(x) = \ln(B_1) + \ln \left( \sum_k \exp \left( - \frac{x}{T_k} \right) \right). \]  

(6)

On the basis of the spectral pyrometry method, we define the reference temperature \( T_s \) as the temperature of a grey emitter whose thermal emission spectrum has a value of its derivative at the point \( x_b \) identical to that in spectrum (6). The temperature \( T_s \) may happen to not belong to the set of image-element temperatures; yet, this temperature can be expressed in terms of this set with the help of formulas (3) and (6):

\[ \frac{1}{T_s} = \frac{\sum_k \frac{1}{T_k} \cdot \exp(-x_b / T_k)}{\sum_k \exp(-x_b / T_k)}. \]  

(7)

Using formula (4), we replace the set of temperatures \( \{T_k\} \) in formula (7) with the levels \( \{b_k\} \) of the image-element signals registered by the digital camera. Following this, we obtain the following formula for determining the reference signal level \( b_s \) that corresponds to temperature \( T_s \):

\[ b_s = \exp \left( \frac{\sum_k b_k \cdot \ln b_k}{\sum_k b_k} \right). \]  

(8)

Then, the set of temperatures \( \{T_k\} \) for the image elements in the measurement volume can be determined by using formula (1). Evidently, here the unknown value of the emissivity \( \varepsilon \) of the material exerts no influence on measurement results.

For adaptation of the spectral-brightness pyrometry method to the measurement of the distribution of dispersed-phase temperature in a plasma flow, we adopt the following model. At fixed operating conditions of the spray facility, the spraying process is assumed to be a steady one, with the expected local values of controlled dispersed-phase characteristics being time-independent quantities. Here, there is no need in tracking the motion and heating of individual particles along their trajectories;
instead, it just suffices to collect sufficient statistical data from a great number of particles at each point of the measurement-volume. The latter allows us to evaluate the spatial distribution of dispersed-phase temperature from the local mean value of this temperature over a coordinate. The stationary model of the spray flow as applied to the entire measurement volume makes it possible to represent the whole ensemble of dispersed-phase particles with a sufficiently large volume of sampled data for estimating the reference signal level $\tilde{b}_s$ and the reference temperature $\tilde{T}_s$. The exposure time of the digital camera $\tau_b$ and the exposure time of the spectrometer $\tau_q$ can be chosen different and, for the same particle ensemble under observation, it suffices that the registration of a frame series be time-matched with the signal integration process in the spectrometer. The latter matching allows reaching a high signal-to-noise ratio in measured spectra of dispersed-phase particle ensembles by setting the time $\tau_q$ to about 1 second and by adopting a value of $\tau_b$ on the order of 10 µs for registration of rapid-particle tracks in the images of a frame series with total observation time $t = \tau_q$. In estimating the reference signal level $\tilde{b}_s$ and reference temperature $\tilde{T}_s$, the fact should be taken into account that the object under observation is not an image element of the measurement volume but, instead, a particle with relative area

$$F = \frac{\pi \cdot d^2}{4}$$

and equivalent signal level of stationary particle $S_p$ [8]. That is why in formulas (7) and (8) we have to pass from summation over image elements to summation over ensemble particles:

$$\frac{1}{\tilde{T}_s} = \frac{\sum n \cdot d_n^2 \cdot \frac{1}{T_n} \cdot \exp(-x_b / T_n)}{\sum n \cdot d_n^2 \cdot \exp(-x_b / T_n)},$$

$$\tilde{b}_s = \exp \left( \frac{\sum n \cdot d_n^2 \cdot S_{p_n} \cdot \ln S_{p_n}}{\sum n \cdot d_n^2 \cdot S_{p_n}} \right).$$

In formulas (10) and (11), $n$ is the number of an ensemble particle that was identified in the frame series, and $d_n$ and $S_{p_n}$ are respectively the relative diameter and the equivalent signal level of the stationary particle with number $n$.

3. Approbation of the method

In the original implementation of the SPB method, the following instruments and means were used: an HD1-1312-1082 digital camera (Photon Focus, Switzerland), an LR-1T digital spectrometer (ASEQ Instruments, Canada), a synchronization circuit of the camera and spectrometer designed around an Arduino microcontroller assembly, a SL-series set of narrow-band optical filters (PhotoOptic-Filters, Russia), and MATLAB software [9]. The measuring complex was approbated while doing research on the plasma-arc wire spraying setup at the Paton Institute of Electrical Welding (Ukrainian National Academy of Sciences, Kiev) and on the determination of performance characteristics of technological processes for the Thermoplasma 50-1 plasma powder spray facility designed around the PNK-50 plasma torch with inter-electrode insert (Institute of Theoretical and Applied Mechanics, Novosibirsk) [10, 11].

After registration of a frame series and optical emission spectrum of the dispersed-phase, MATLAB means were used to reveal the possible presence of plasma-induced lines in the working spectral region of the digital camera. If such lines were revealed, then the optical filter was changed for another one, and the registration was performed once again. Automated change of the spectral
region of the digital camera is possible in using, in the complex, KURIOS-WB1(/M) acousto-optic or liquid-crystal tunable filters with a re-adjustment time of 40 ms.

The thermal emission spectrum over the working region in variables (2) was used to evaluate the dispersed-phase reference temperature in the measurement volume. For suppressing the effect due to the transmittivity of plasma-flow medium on the registered signal level, digital filtration and morphologic-analysis methods were employed to remove from measured data the variable background with a heterogeneity scale one order of magnitude greater than the particle size. Then, individual tracks were recognized in the images; from the tracks, such characteristics of the particles as their position in the flow, velocity, direction of motion, diameter, and equivalent signal level of stationary particle were determined [12]. Afterwards, for the ensemble of the particles, the reference signal level was calculated by formula (11), and the temperature of all the particles, by formula (1). Selection of the particles over the coordinate of the spray flow projection has allowed us to obtain local sampled datasets for dispersed-phase properties and construct the maps of mean values and dispersions (Fig. 2).

![Fig. 2. Maps of dispersed-phase properties in the spray flow of the PNK-50 plasma torch (a – mean particle velocity, m/s; b – mean particle temperature, K; c – relative concentration of particles, %).](image)

The volume of sampled data in the evaluation procedure for \( \tilde{b}_3 \) and in the plotting of the maps of dispersed-phase properties amounted to \( 5 \times 10^5 \div 10^6 \) particles that were identified in 10000 image frames. A parallel data-processing algorithm implemented in MATLAB software has ensured an
analysis rate of 3500-5000 particles per second. In the course of the analysis, the inaccuracy in measuring the dispersed-phase temperature in plasma flow by the spectral-brightness pyrometry method was estimated to be at a level of 0.75-1.5%.

4. Conclusions
The spectral-brightness pyrometry method can be used to control the spatial dynamics of the thermodynamic temperature in fast processes. The sensitivity of the method is comparable with the sensitivity of the brightness pyrometry approach. Moreover, the inter-relation between the signals in the brightness and spectral channels permits an in-situ calibration of measuring instruments while observing the objects under study. The latter makes the developed pyrometric method an invariant one with respect to the emissivity values of substances in condensed state. An additional analysis of the spectrometer signal is used for verification of the thermal nature of the optical emission in the working band of the camera optical filter, and it helps in excluding inadequate measured data. The inaccuracy in determining the temperature of individual particles by the spectral-brightness pyrometry method proved to be less than 2%. This work was supported by the Russian Foundation for Basic Research under Grants Nos. 14-08-90428 and 15-48-00100.

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