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New High-Speed Combination of Spectroscopic And Brightness Pyrometry For Studying Particles Temperature Distribution In Plasma Jets

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Abstract. Up-to-date methods and devices for temperature of dispersed phase control in high-temperature flows are considered. Possibilities of building pyrometric systems using available modern equipment are discussed. The new pyrometric method based on registration of a wide spectral range of radiation is proposed and implemented. Results of particles temperature measurements during plasma treatment of zirconia powders are presented.

Keywords: plasma flow diagnostics; thermal radiation; particles temperature; pyrometry.

Introduction.

Measurement of objects' temperature based on registration of their thermal radiation spectrum is a major challenge in various fields. Similar problems are solved in astrophysics, nano-scale investigations and routine industrial processes. Distinctions in measurement procedures consist in technical details: range of measured temperatures, spectral range of registered electromagnetic radiation, applied radiation detectors.

Materials and Methods.

The range of temperatures measured by optical pyrometry methods is defined first of all by spectral sensitivity range of a detector. Conventional silicon elements (sensitivity range 300-1000 nm) allow measurement of temperatures from 1000 K and above. Recently InGaAs elements (sensitivity range 900-1700 nm, at raised In concentration – up to 2500 nm) became widely available, which provide measurement of temperatures from 250-300 K and above.

All the methods of optical pyrometry are based on implementation of Max Planck's law of radiation. Most of the up-to-date detectors of radiation are semiconductor systems which count photoelectrons produced due to internal photoelectric effect. Therefore it is convenient to use the law of radiation of black body (BB) in the following form: number of photons irradiated in the semi-infinite space from the unit surface of BB in the unit range of wavelengths in the unit time period is given by formula

$$r(\lambda,T)=\frac{c_1}{\lambda^4}\frac{1}{1-e^{c_2/\lambda T}} \quad [\text{pcs/(mkm}\cdot\text{mm}^2)], \tag{1}$$

where c_1=1.884·10^{21} pcs·mkm^3 /mm^2, c_2=14 388 K·mkm, λ – wavelength of radiation in mkm, T – temperature of BB. Spectral brightness of real irradiator $b_{\lambda,T}$ is expressed in terms of $r_{\lambda,T}$:

$$b_{\lambda,T}=\varepsilon_{\lambda,T}\cdot r_{\lambda,T}, \tag{2}$$

where $\varepsilon_{\lambda,T}$ – spectral emissivity of a given material at a given temperature T.

When radiation of a real object at the actual (thermodynamic) temperature T_{act} is registered and measured at a wavelength λ_0 the brightness temperature T_{br} of the object is determined as a temperature of BB at which it has the same spectral brightness at the wavelength λ_0 as the investigated object with temperature T_{act}:

$$b(\lambda_0,T_{act})=r(\lambda_0,T_{br}). \tag{3}$$

Registration of object's thermal radiation at two different wavelengths λ_1 and λ_2 allows to determine a its color temperature T_{clr}, which is the temperature of BB at which the relation of spectral brightness $r(\lambda,T_{clr})$ at wavelengths λ_1 and λ_2 is the same as determined in measurements of radiation of real object with actual temperature T_{act}:

$$\frac{b(\lambda_1,T_{act})}{b(\lambda_2,T_{act})}=\frac{r(\lambda_1,T_{clr})}{r(\lambda_2,T_{clr})}. \tag{4}$$

It is quite obvious that the actual temperature of the object T_{act} will differ from determined values of brightness temperature T_{br} and color temperature T_{clr}, when spectral emissivity $\varepsilon_{\lambda,T}$ of material depends on wavelength. The relation of these temperature values is expressed with the following formulas [1] considering Wien's approximation:

$$\frac{1}{T_{br}}=\frac{1}{T_{act}}+\frac{\lambda}{c_2}\ln\frac{1}{\varepsilon(\lambda_0,T_{act})}, \tag{5}$$

$$\frac{1}{T_{clr}}=\frac{1}{T_{act}}+\frac{\ln(\varepsilon_1/\varepsilon_2)}{c_2\left(1/\lambda_1-1/\lambda_2\right)}, \tag{6}$$

where ε_1 и ε_2 – spectral emissivity of the material at the λ_1 and λ_2 wavelengths respectively.

Traditional pyrometric methods of absolute (brightness pyrometry) and relative (color pyrometry) temperature measurements exhibit high errors related to inaccuracy of radiation intensity registration and presence of dust and fumes in the optical channel. Moreover calculation of the actual temperature from brightness or color temperature requires knowledge on spectral emissivity of the investigated material, which often is unknown for new materials. Typically accuracy of such methods in favorable laboratory conditions is estimated as 10-15%.

Optical sensing devices. Measurement of temperature of dispersed phase particles in plasma flows is complicated because of small size high velocities of the objects and strong selfradiation of plasma. Present market of optical sensing systems for particles temperature and velocity measurements offers several devices, all of them implement in one or another way two-color pyrometric method: DPV, Accuraspray (Tecnar, Canada), Spectraviz (Stratonics, USA), SprayWatch (Oseir, Finland). Typical errors in determination of average particles temperature make 600 K when measuring temperatures in 2500-3000 K range [2]. Apparently this is methodological limit of this approach. This example clearly demonstrates necessity in development of new diagnostic systems for two-phase flows.

Full (wide) spectrum pyrometry is distinguished by registration of radiation intensity $b(\lambda)$ using several thousands of detectors – elements if CCD array. This feature allows directly during monitoring process make sure that registered spectrum has thermal origin [3]. Even simle implementation of two-color pyrometry method for various pairs of wavelengths in registered spectrum allows to determine statistically most probable temperature of the object with accuracy 3-5% [4]. Even more accurate temperature determination can be achieved using fitting the Planck's function to the registered spectrum. The «laboratory condition» accuracy of this method is approximately 2 %.

Registration of two-phase flows movement with high-speed CCD-cameras allows to combine in a single device tools for single particles velocity control [5, 6] and brightness or two-color pyrometer [7, 8]. In a real technological process with a priori determined optimal regimes implementation of video system provides valuable possibility of a jet geometry and particles trajectory control which indicate equipment state of health [9-11].

Methodology of calibration of brightness and color pyrometers based on CCD-matrices is well developed nowadays [12, 13] and provides mentioned above temperature measurement accuracy values. Integration of spectral devices into monitoring systems should start new period in their evolution. High accuracy of temperature determination of spectral devices allows to use them as autonomous intrinsic calibration systems. However the future of spectral sensors is summation of the signal over the scoping region (in contrast to video systems) which requires to solve a problem of reduction particles temperature distribution from their collective radiation spectra. The approach to solution of this problem is already formulated in [2, 14].

Experiment and discussion. The goal of experimental work was optimization of regime parameters of hollow powder production process [15] and measuring temperature of zirconia particles in various cross-sections of a plasma jet. Plasma gun designed in ITAM SD RAS was used in following configuration: anode 10 mm, nitrogen flow rate 30-50 slpm, arc current 150-200 A, Metco 204 71-80 mkm zirconia powder feedrate 2 kg/h, two-side radial injection of the powder.

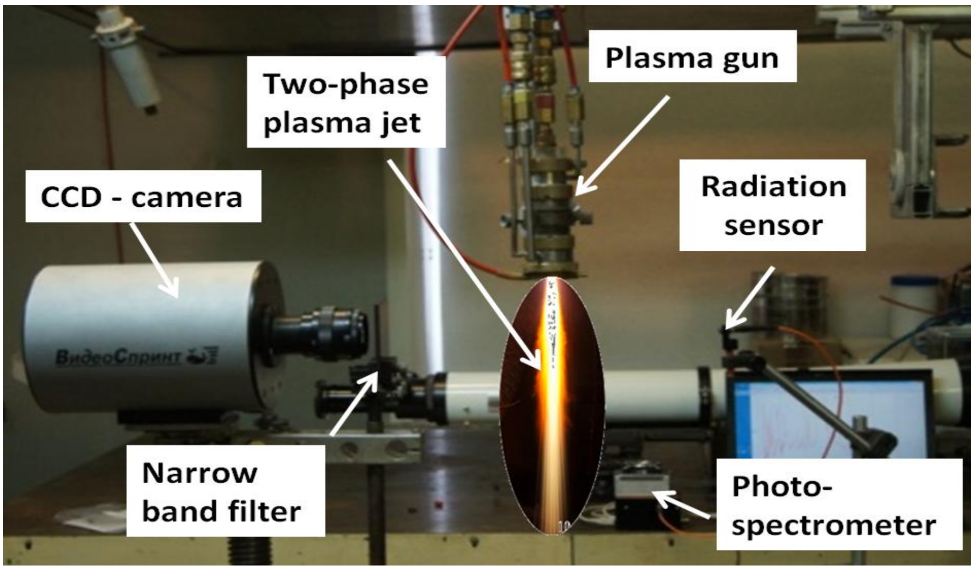

Figure 1. Plasma jet and combined registration system.

Registration of powder particles trajectories in plasma flow was carried out with high-speed

(500-50000 fps) CCD- camera Videosprint (Videoscan, Russia) (fig.1). Narrow band optical filter was used to suppress plasma radiation. Simultaneously the spectrum of particles thermal radiation was registered using LR1-T (Aseq, Canada) spectrometer using cooled silicon Toshiba TCD1304AP CCD array with sensitivity spectral range 300-900 nm.

After the optimal regime for plasma powder treatment was determined and fixed the camera was used as process quality control system. Fig. 2 demonstrates an image of high-temperature flow with tracks of irradiating particles.

Figure 2. Video image of two-phase plasma flow with zirconia particles tracks. Nitrogen flow rate 45 slpm, arc current 200 A, arc voltage 190 V, powder feedrate 2 kg/h. Exposure time 40 mks.

Temperature of the particles was determined using analysis of their collective thermal radiation spectrum. Scoping region of the sensor covered a section of the jet 1 cm long. During spectrometer sensor exposure time (12-100 ms) hundreds of particles are crossing the scoping region and each of them has its own temperature. Considering all the particles have the same size, cross-section area (71-80 mkm powder was used) and dwell time, the registered spectrum can be expressed in the following form:

$$N(\lambda) = K\int_0^\infty r(\lambda,T)\cdot f(T)dT \quad (7)$$

Here $f(T)$ - particles number distribution function over the temperatures, K - scaling coefficient taking into account all the geometrical properties of the optical path. The spectral emissivity of zirconia is unknown, therefore it wasn't considered in calculations.

It is known from the practice of thermal spraying that particles distribution over the temperature (as well as over the velocity) has Gauss shape. Therefore the following formula was used:

$$f(T) = \frac{1}{\sigma\sqrt{2\pi}} EXP\left(-\frac{(T-T_0)^2}{2\sigma^2}\right), \quad (8)$$

where T_0 - is the average temperature of the distribution, σ - width of the distribution. Fig. 4, *a* shows the spectrum registered at the distance of 15 cm downstream from the nozzle and the calculated best-fit curve corresponding to parameters of the distribution T_0 =2472 K, σ =424 K (fig. 4, *b*).

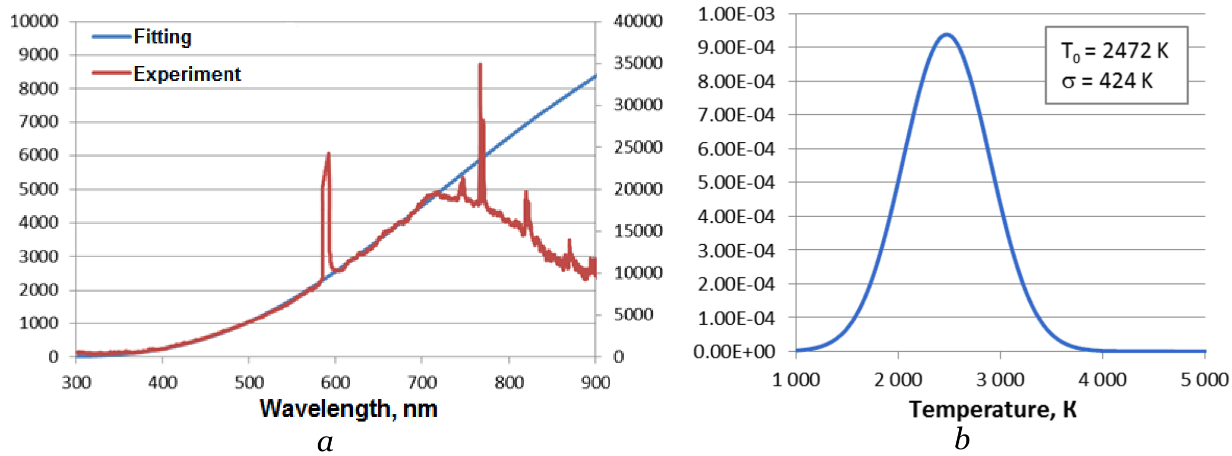

Figure 3. Registered and calculated collective thermal radiation spectrum (a) and calculated temperature distribution of the particles ensemble (b).

Similarly parameters T_0 и σ where found for various cross-sections of the plasma jet. Additionally «maximum» temperatures for each cross section of the jet where found by fitting the Planck's function to the 350-420 nm range of the registered spectrum. Fig. 4 shows evolution of measured average and maximum temperatures along the length of the jet. Error bars near average temperatures (circles) correspond to the values of parameter σ in determined distributions. As one can see average and maximum temperatures of the particles decrease from the distance 5 cm downstream from the nozzle. Fig. 4 also presents results of particles temperature calculation using theoretical model [16] and plasma jet profiles calculated with CFD software Ansys Fluent. All the calculations were performed for spherical zirconia particles with diameter 75 mkm and porosity 50 %. Radial injection velocity of particles was varied in calculations: 4, 6, 8 m/s. The dynamics of calculated temperature change along the jet length corresponds more closely to the maximum measured temperatures.

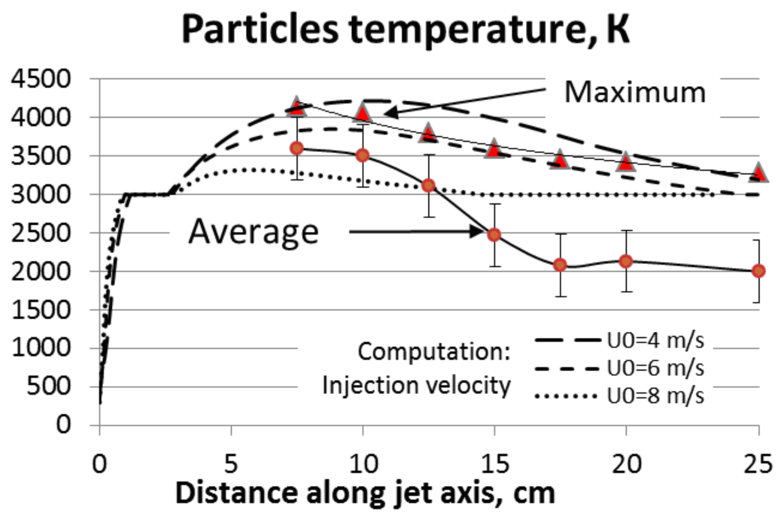

Figure 4. Comparison of zirconia particles average temperature (circles) and maximum temperature (triangles) measurements with calculation results (dash lines).

Conclusion. The conducted analysis of various optical pyrometry methods demonstrates that wide spectral approach allows not only to increase accuracy of temperature measurements but also to provide information on particles temperature distribution. In the present work an example of combined implementation of high-speed video system and visible range spectrometer is given. This system was used for control of zirconia powder temperature state during hollow powder production process. Development of the described monitoring complex will evolve into integrated system for particles temperature and velocity measurement based on widely available CCD-sensors.

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Новая быстродействующая комбинация спектральной и яркостной пирометрии для изучения температурного распределения частиц в плазменных струях

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Аннотация. В статье рассмотрены современные методы и устройства для температуры контроля за дисперсной фазой в высокотемпературных потоках. Обсуждаются возможности создания быстродействующих систем пирометрии, используя доступное современное оборудование. Показана реализация нового метода исследования температурного распределения частиц, основанного на регистрации широких пределов спектра излучения. Представлены результаты измерений температуры частиц во время плазменной обработки порошков двуокиси циркония.

Ключевые слова: плазменная диагностика потока; тепловое излучение; температура частиц; пирометрия.