

The optical control system of dispersed phase properties in thermal spray process

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Abstract. The models of measuring the velocity and temperature of particles using the processing of their track images are introduced. The method of brightness pyrometry of moving objects uses the calibration procedure based on the static temperature standard. Performance of the statistical analysis of thermal data by means of optical control system of the particles properties in gas-thermal spraying flow equals to 2200-2700 particles per second. Investigation of stationary plasma spraying process allowed to obtain the distributions of velocity and temperature of particles over the volume of spraying jet. The error in determining the velocity of the particles was 1%, and the error in determining the temperature is 3%.

1. Introduction

The effective way of deposition of protective and functional coatings onto the machine parts is realized by means of the various thermal spraying technologies [1, 2]. They include plasma-arc, plasma, detonation and other types of spraying technology. Velocity and temperature of the particles are the "key" physical parameters that define the basic characteristics and quality of the coating as a whole. The control of these parameters allows to maintained of the required quality of spraying coatings, optimize the operation modes of the processing station to improve the efficiency of use of raw materials, and also to carry out the adaptation process of technological mode at the transition to processing station of another class. Modern optical measuring systems based on methods of non-destructive testing and measurements, are able to provide the information required for the technology [3, 4]. However, it should be noted that modern devices of optical control of speed and temperature of particles have certain disadvantages: low accuracy; inability to use of devices for the flows with a high concentration of the dispersed phase, too slow response. The most difficult task is to measure the temperature. The solution of this task requires the development of new methods with high resolution [5-10].

This paper presents the system for optical control and measurement of key physical parameters of the dispersed phase in a heterogeneous flow in thermal spray process. This system allows to control the operation regime stability of technological facility.

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2. The optical control system of properties of dispersed phase in thermal spray flow

The control system is based on the idea of registration of particles radiation in the form of a series of images of their tracks and determining the parameters of the individual particles through these tracks analysis. In the stationary state of operation of the spraying facility the statistical characteristics of the dispersed phase of spraying jet in any place it should remain constant in time. Then evaluation of these characteristics can be performed through selection of particles which have been identified in video frames.

The control system comprises two data channels. The first channel is used to collect the thermal data about the brightness temperature of the dispersed phase of spraying flow, and the second channel controls its spectrum and provides the spectral temperature [3]. The sensor of first channel is the video camera with information bandwidth 1 Gb/s. Processing of this information is complicated so it is unrealizable to implement at hardware level in the physical device. Therefore, the structure of the control system was built using the concept of virtual instruments, which provides interaction between the data acquisition module and the data processing module. The data acquisition module integrates the optical subsystem, streaming camera HD1-1312-1082-G2 (PhotonFocus, Switzerland) of visible and near IR range with Gigabit Ethernet interface and high-speed spectrometer LR1-T (ASEQ Instruments, Canada). To implement the data processing unit is used MATLAB software which provides powerful tools of conversion of multidimensional signals based on the technology of parallel computations. Block diagram of the control system is shown in Figure 1.

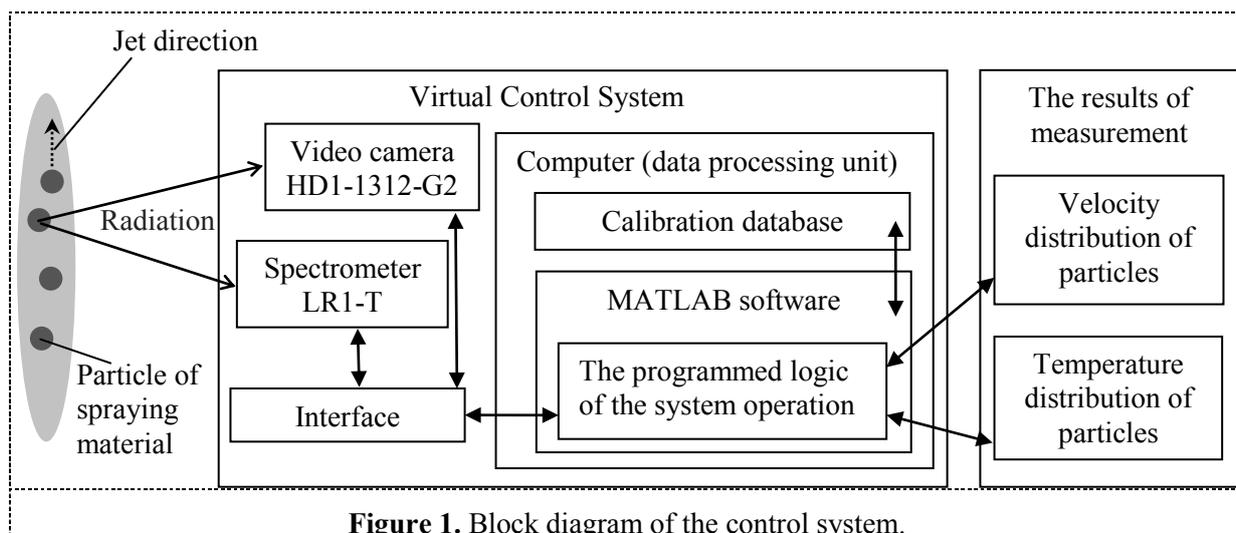


Figure 1. Block diagram of the control system.

Monochrome camera HD1-1312-1082-G2 is based on a CMOS matrix of 1312x1082 pixels with spectral sensitivity range of 400-1000 nm. The signal of CMOS matrix is represented by 12-bit digital code, and interface real-time allows transmit data to a computer with a frequency of 55 frames per second. Camera driver supports the standard MATLAB environment interface and allows to use it as a source in a pipeline processing. To provide temperature measurements by means of HD1-1312-1082-G2 video camera bandpass filter SL-575-50 (LLC "Photooptik", Russia) with a central wavelength of 575 nm and a half-width of 50 nm was added into its optical channel. In addition, on the automated test bench was developed for calibration and correction of nonuniformity of camera sensitivity. Composition and method of operation of the automated test bench presented in [4].

Digital spectrometer LR1-T is based on the linear CCD-sensor of 3648 photocells and includes thermoelectric cooler to -35 °C. Spectrometer provides measurements in the spectral range 200-1100 nm. Digital spectrometer data represented a 16-bit digital code that is transferred to the computer by the interface USB 2.0. To display spectrometer in MATLAB-software was developed the M-class of facilities "aSpectr", which represents it as a virtual instrument with a set of properties and methods. To

measure the spectral temperature was performed the correction of the nonuniformity of detector sensitivity by means of the automated test bench and methods [3].

3. The method of measuring the velocity and temperature of particles of the dispersed phase in the thermal spray flow

During thermal spray process particles of size 10-100 microns are heated to temperatures of 1000-3500 K, while remaining in the condensed phase (in the form of liquid droplets of spherical shape), and spectrum of their heat emission can be registered in the range from 300 to 1000 nm.

The following method was used for velocity measuring of particles moving in the thermal spray flow. The image of the particle stream is projected onto the matrix photodetector of camera that is placed in the focal plane of the optical system. Photodetector works on the principle of charge accumulation during the exposure time τ . The value τ is chosen so that the particle can undergo a straight path, the length of which is 20-30 times greater than particle diameter. The camera registers the trajectory of particle-the track but not a particle itself. The image of a spherical particle will be the area of a circle of diameter D , and the track of a moving particle should look as rounded rectangle. The length of the movement of the circular image of the spherical particle is equal to

$$L = Z - D, \quad (1)$$

where Z - the maximum (longest) size of the rounded rectangle and velocity of the particle is equal to

$$v = \mu \cdot L / \tau \quad (2)$$

where μ - scaling factor that converts the length of the track in pixels into the real path of particle.

By means of MATLAB-software for each video-frame was created a mask and performed morphological analysis which tests the connectivity of the binary image areas and is performed the image division into objects corresponding to the individual tracks. Selected tracks that touch the frame boundaries are removed from the image, since it is impossible to find their length. Each selected object is analyzed for the definition of the apparent diameter of the particle track length, the coordinates of its center, orientation, brightness. In order to exclude overlaid tracks objects are filtered in according to the length, diameter and the ratio of maximum to average brightness. Objects which do not satisfy the filter parameters are deleted from the image and the residual objects are identified as tracks (Fig. 2).

At first, the estimates of mathematical expectations of parameters of the particle tracks are calculated with a significance level of 0.05. Tracks whose parameters fall within the appropriate confidence intervals, believed to be significant, but the residual tracks are discarded. Velocities of the particles, and hence the velocity distribution of particles, are determined by the parameters of the identified tracks according to formula (2).

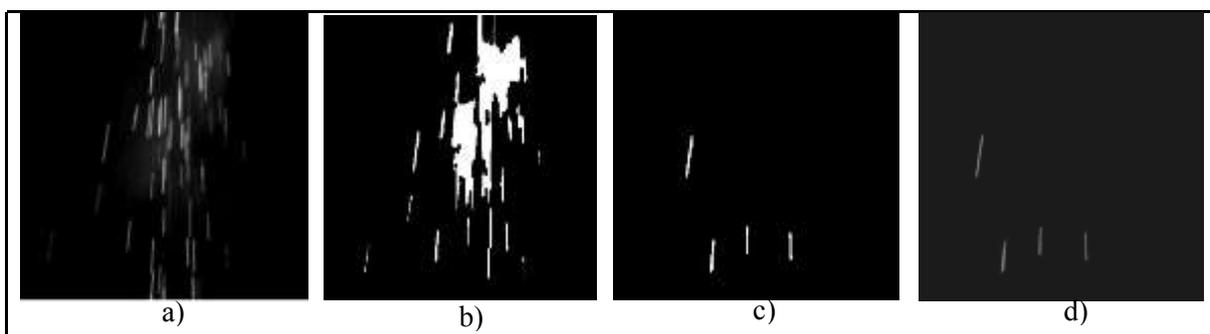


Figure 2. The video frames processing steps: a - the original image; b - the result of applying a binary mask; c - the image with probable tracks; d - the processed image with the identified tracks.

Given the range of the measured temperature 1000 - 5000 K and the "effective" wavelength of filter $\lambda_f = 575$ nm (filter SL-575-50) the Wien approximation can be used to describe the spectral brightness of the particle radiation. The parameters of the optoelectronic channel in the process of

measuring are fixed, and the photodetector signal is proportional to the energy of the particle radiation during the exposure and depends only on the temperature of the observable object:

$$F(T) = K \cdot \varepsilon(T) \cdot \exp\left(-\frac{C'}{T}\right), \quad (3)$$

where K - constant that includes the coefficient of optoelectronic conversion, $C' = (h \cdot c)/(k \cdot \lambda_f)$, c - the speed of light, h and k - Boltzmann and Planck constants, $\varepsilon(\lambda_f, T)$ - spectral emissivity of the particles at the effective wavelength λ_f . In the calibration process by means of the temperature lamp TRU-1100-2350 for each signal value F of the photoelectric cell on the basis of (3) the brightness temperature T_b is calculated and these data are saved in a table:

$$(F_1, F_2, \dots, F_{255}) \Leftrightarrow (T_{b1}, T_{b2}, \dots, T_{b255}). \quad (4)$$

Denote F_p - signal of the sensor photocell recorded during the exposure time for motionless (stationary) particle, and S_p - the area of its image. If during the observation particle temperature remains constant, then the energy of the thermal radiation emitted by it in equal intervals of time, will be the same. Under the assumption of uniform distribution of the signal level of the photocell on the area S_{tr} of the track, must satisfy the relation:

$$F_p \cdot S_p = F_{tr} S_{tr}. \quad (5)$$

The area of the model image of motionless particle and her track respectively are equal

$$S_p = \frac{\pi \cdot D^2}{4}; \quad S_{tr} = \frac{\pi \cdot D^2}{4} + L \cdot D. \quad (6)$$

Denote T_{tr} - the brightness temperature, which corresponds to the signal level F_{tr} according to formulas (3) and (4). Then, based on (3), (5), (6) the temperature of the particle can be determined as follows:

$$\frac{1}{T} = \frac{1}{T_{tr}} + \frac{1}{C'} \left(\ln \varepsilon(T) - \ln \left(1 + \frac{4}{\pi} \cdot \frac{L}{D} \right) \right). \quad (7)$$

Formula (7) allows to measure the thermodynamic temperature of moving particles with the parameters of the tracks L , D , and with the known dependence of the spectral emissivity of the material, and the thermal calibration of photodetector can be performed on a motionless temperature standard. Otherwise, their brightness temperature is determined. Further, similar to velocity calculation, the confidence intervals of the track parameters are estimated with a significance level of 0.05 and then statistical filtering is performed.

4. Results and discussion

Research carried out by means of optical control system at the Paton Electric Welding Institute NASU was focused on the study of characteristics of the dispersed phase of the spraying jets to optimize the operating regimes of plasma-arc facility "Plazer". In the coating process the anode-wire was fed with constant rate after the plasma torch nozzle [11, 12]. Under the action of the arc and the plasma gas the wire of different composition was melted, fragmented into droplets the size of 5-50 μm and they were accelerated to the treated surface. The sight window of the control system was 2,9x2,4 cm. The distribution of particles parameters over the spraying flow in the area 16x8 cm was investigated using scan of the jet with the optical module. The spectrometer was used to ensure the absence of the plasma band-emission lines in the spectral range of thermal imaging channel and to measure the spectral temperature - maximum thermodynamic temperature of the dispersed phase in the thermal spray flow. After processing of video files recorded in a stationary operation regime of the spraying facility and merging the analysis results the frequency distributions of parameters of the dispersed phase for the entire jet were obtained (Fig. 3).

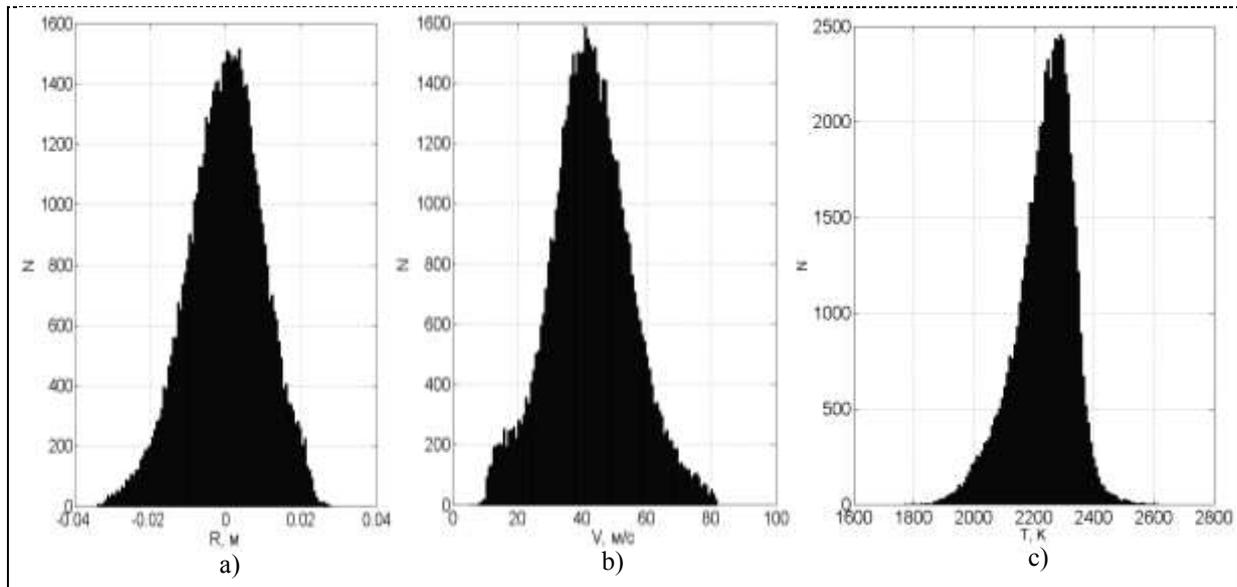


Figure 3. Frequency distributions of the dispersed phase parameters in the spraying jet (steel wire diameter 1.6 mm, arc current 220 A): a – radial coordinate (m), b – velocity (m/s), c – temperature (K).

A sample consisting of 60000 identified tracks was used to construct statistical distributions. The distribution of particles radial coordinate (Fig. 3, a) demonstrates the asymmetry of the jet and determines the spraying spot and coating deposition rate. Distributions of particles velocities (Fig. 3, b) and temperature (Fig. 3, c) allows to estimate the dynamic range and variation ratio of these characteristics providing a base for thermal and kinetic parameters of the spraying jet optimization.

The spatial dependences of the statistical estimates (average values) of temperature, velocity and direction of motion of the particles are presented in Fig. 4, a-c. The number of particles identified in various jet positions is shown in Figure 4, d.

Particles velocity and temperature spatial dependences reflect their motion and heating dynamics. The obtained results allow us to calibrate the mathematical models describing the processes of plasma-arc spraying, optimize spraying distance, to produce the transfer of technological spraying regime between facilities of different classes, as well as to optimize the operation regime of a given spraying facility and optimize its design.

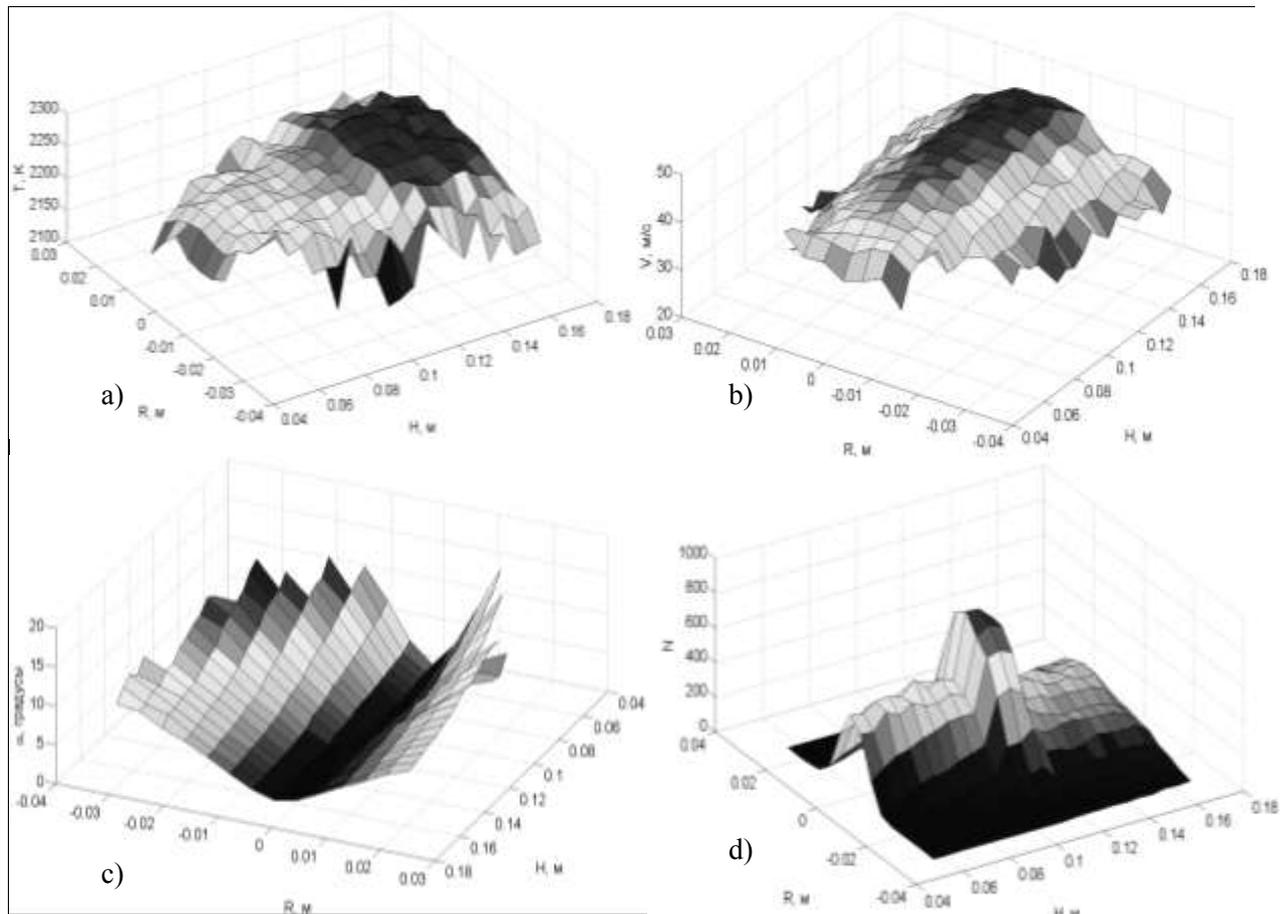


Figure 4. The spatial dependence of dispersed phase parameters in “Plazer” facility spraying jet: a – temperature (K), b – velocity (m/s), c - motion angle (degrees), d – number of identified particles of dispersed phase (pieces). Axis notations are as follows: R – radial distance from the axis of the jet (m); H – axial distance from the nozzle (m).

The above method of constructing histograms of the particles velocity (and temperature) uses the traditional statistical approach counting velocities of individual particles corresponding to different spatial and temporal positions in the jet (different particles of the accumulated statistics are being registered in large time intervals).

The following describes the different approach [13], in which the histogram of the velocities is constructed by the individual image frame (for short exposure time) and each column is obtained by averaging parameters in a certain cross-section of the jet.

Experiments were conducted in Khristianovich Institute of Theoretical and Applied Mechanics SB RAS at the spraying facility using 50 kW DC plasma torch for production of hollow ceramic spheres [14] from yttria-stabilized zirconia (YSZ) feedstock powders of 50-56 mkm diameter (204B, Sultzer Metco). The regime was as follows: plasma-forming nitrogen flow rate 30 slpm, arc current 150–200 A (voltage 180–190 V), thermal efficiency 60 %, anode diameter 10 mm, feed rate of powder 6 kg/h, double side radial powder injection.

In this technique the particles image processing unit is implementing a consistent pipelined processing consisting of five procedures [13]: the smoothing by means of the spatial Gaussian filter, the computation of the brightness profile derivative function of the image by means of the discrete differential Sobel operator, thinning of tracks boundaries, dual threshold filtering, parameterization of tracks by Hough algorithm. The particle velocity is calculated according to the formula (2) and

estimated track lengths L . Then, in each cross section of the jet are determined the average values of the particle velocities and the histogram of particle velocity distribution (along the axis of the jet). Figures 5 and 6 demonstrate examples of image processing, calculating the particle velocity distribution and the particles density distribution in the flow.

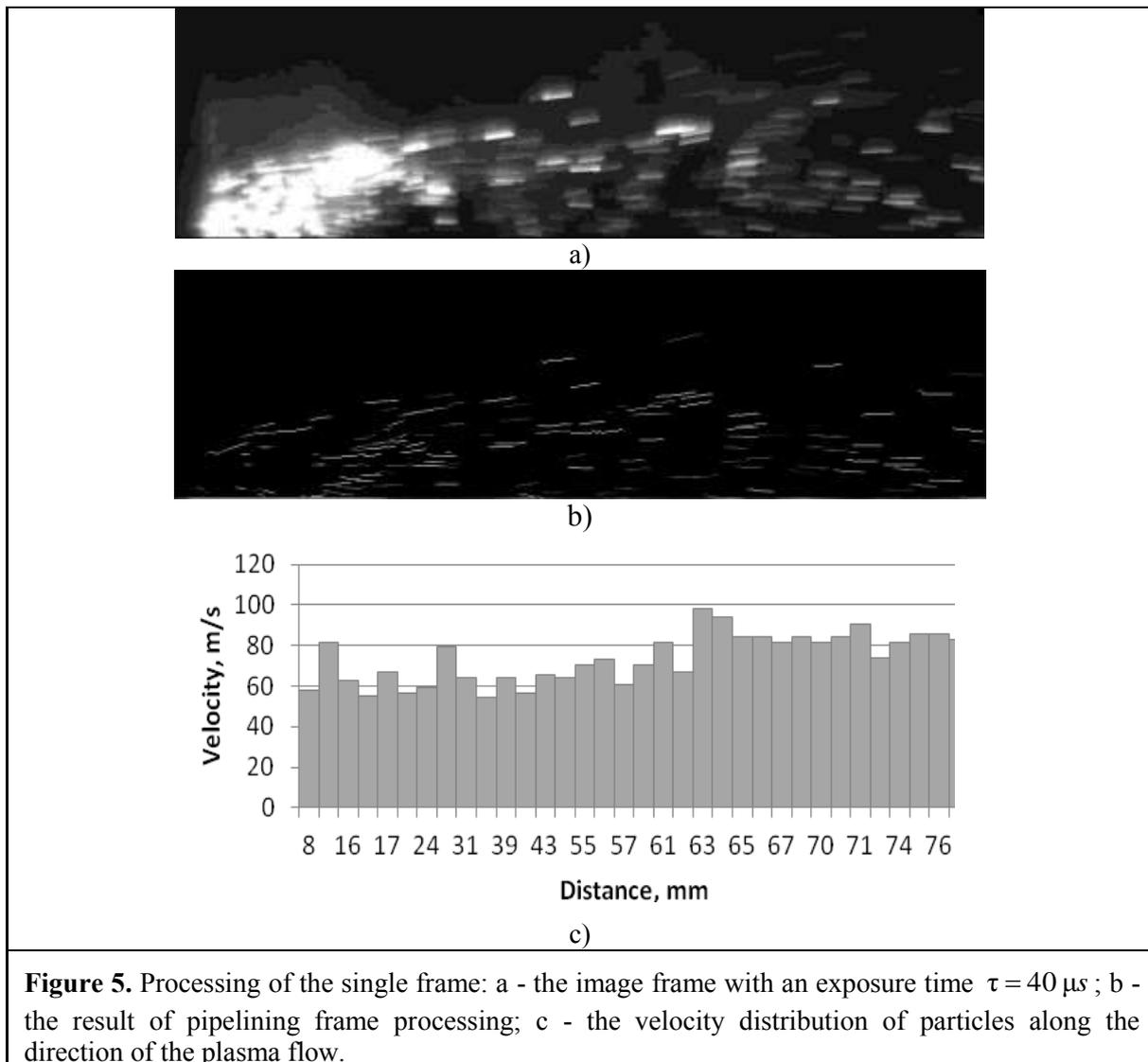


Figure 5. Processing of the single frame: a - the image frame with an exposure time $\tau = 40 \mu\text{s}$; b - the result of pipelining frame processing; c - the velocity distribution of particles along the direction of the plasma flow.

As can be seen from fig. 5, c the particle velocity has stabilized at the distance 65 mm from the nozzle of plasma torch. For a small time exposure of frame (fig. 6, a) the tracks are presented as points (particles) and after appropriate image processing in different cross sections of the flow this assumption allows to estimate the relative portion of particles (particle flow density, fig. 6, b).

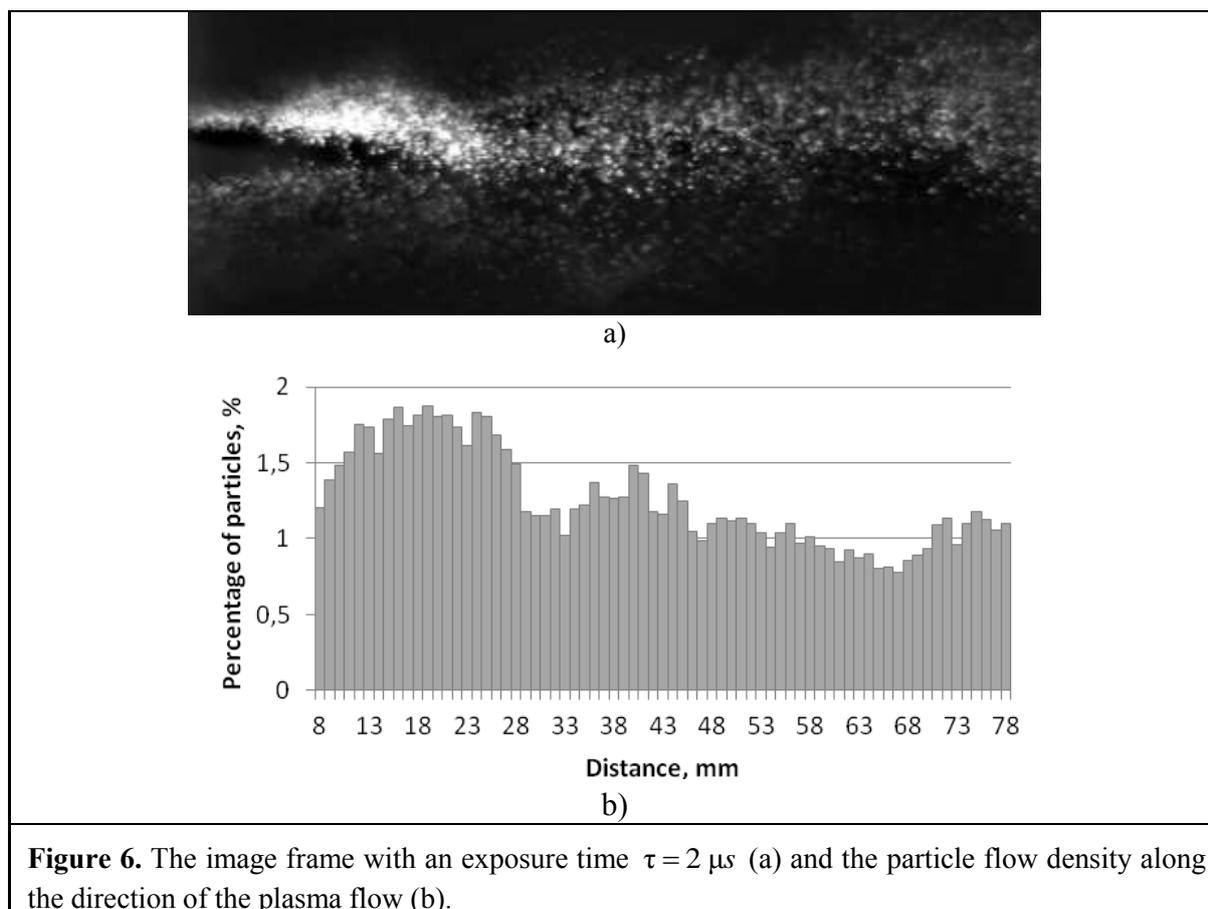


Figure 6. The image frame with an exposure time $\tau = 2 \mu\text{s}$ (a) and the particle flow density along the direction of the plasma flow (b).

Analysis of fig. 6, b uncovers the "wavelike" nature of the particle flow density along the axis of the plasma jet (sequence of "compactions" and "decompactions"), which provides a tool for of stationarity control during facility operation.

5. Conclusion

The system of optical control of velocity and temperature of the dispersed phase in the thermal spray flow was developed on the base of the camera HD1-1312-1080-G2, the spectrometer LR1-T, and signal processing module in the environment of MATLAB. The models for measuring velocity and temperature of the spraying particles from the images of their tracks are presented. The method of the brightness pyrometry of the moving objects based on a calibration by the motionless temperature standard source introduced. The error in measuring the velocity of the particles is 1%, and the error in measuring the temperature is estimated by authors to be 3%. Performance of thermal video-data analysis by means of optical control system is determined to be 2200-2700 particles per second. The developed methods for particles velocity and temperature distribution evaluation allow to investigate the stationarity of the spraying facility operating regime. The optical control system can be used to control the spraying process in the real-time, for the optimization of the technological regime of improving of the spraying facility. The work was performed as part of a joint project of Russian Fund for Basic Researches (№14-08-90428) and National Academy of Sciences of Ukraine (№ 06-08-14).

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