Determination of distributions of key physical parameters of plasma jet particles by means of image stream processing during high-speed video filming

V I Jordan¹-², D I Kobelev¹

¹Department of Computing Techniques and Electronics, Altai State University, 61, Lenin ave., Barnaul, 656049, Russia
²Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch of RAS, 4/1,

E-mail: jordan@phys.asu.ru

Abstract. During the filming by a high-speed video camera, the images of a particle flux moving in a plasma jet during the spraying of powder coatings on machine parts are recorded. The distributions of key physical parameters of particles in the flux cross sections of the plasma jet with the help of algorithms of the filtering and selection of the particle tracks from the images are computed. The distribution of the particle velocities along the jet axis was computed. The processing of the image stream with a small frame exposition time allowed determining the particle bulk density distribution along the plasma jet axis. As a result of images processing for cross section at the end of the flux the dependence of differential density distribution of particles vs. orientation angle of their tracks directions relative to the flux axis has been obtained.

1. Introduction

One of the most effective technologies in the field of material science is the plasma spraying of coatings on the machine parts by using microdroplets of melts of various powder materials. In order to produce coatings with desired properties and to predict the coating quality, it is necessary to measure the key physical parameters of plasma jet particles in the technological chain "plasmatron - jet - coating". The most important parameters of the spray jet are the distributions of particle velocity and particle temperature in the cross sections of the jet as well as the particle bulk concentration distribution (the particle bulk density distribution) not only in the center but also at the periphery of the jet [1-4]. Modern high-speed video cameras, based on modern matrices of photodetectors and microprocessor systems, allow detecting the optical radiation of heated particles moving in technological jet at the velocity of 100 m/s and more [1-4]. Figures 1 and 2 show the fragments of optical images of particle flux (drops of ceramic melt) registered by a high-speed video camera for various frame exposition time (the track length is proportional to the exposure time).

The particle velocity is defined as the ratio of the track length $L$ to the exposure time of frame $\tau$, multiplied by a scale factor $\mu$, which converts the track length into the real path traversed by the particle:

$$ v = \mu \cdot \frac{L}{\tau}. $$

(1)
Thus, the problem of finding the particle velocity distribution is reduced to the problem of selection of the particle tracks from the optical image, the assessment of their sizes and calculation of particle velocity from equation (1).

\[ u = \frac{v}{y} \]

Figure 1. Fragments of the optical image of the particle flux (exposure time of frame is 10 μs): (a) particle flux (set of tracks) at the plasmatron exit; (b) part of the tracks on an enlarged scale.

Figure 2. Inverse image of the laminar part of the particle flux on an enlarged scale (corresponding to figure 1(a)).

2. Determination of distributions of key physical parameters of plasma jet particles by means of image stream processing

The isolation of particle tracks from the image of the plasma jet particle flux can be produced by methods of the image segmentation. In general, the image segmentation is one of the most complex image processing tasks. In the first step of image processing is necessary to reduce the influence of noise. The presence of noise is more pronounced in the vicinity of the particle tracks (figures 1 and 2).

To reduce the image noisiness, the function of pixel luminance \( F(x, y) \) undergoes a smoothing by using the cyclic convolution (2):

\[
F_G(x, y) = g(x, y) \ast F(x, y) = \sum_{i=-2}^{2} \sum_{j=-2}^{2} g(i, j) F(x+i, y+j),
\]

where \( g(x, y) \) is the Gaussian spatial filter (3) with \( \sigma = 1.4 \). The filter window contains 5x5 pixels, i.e. the variables \( x \) and \( y \) are the integers: -2, -1, 0, 1, 2:

\[
g(x, y) = e^{-\frac{x^2+y^2}{2\sigma^2}}/(2\pi\sigma^2).
\]

The analysis of the luminance jumps in the image allows to select the particle tracks. The luminance jumps are calculated by the partial derivative of the pixel luminance function \( F_G(x, y) \) along the vertical direction \( Y \) (top to bottom) for each \( x \)-coordinate along the jet axis. The cyclic convolution (4) of discrete differential Sobel operator with the pixel luminance function \( F_G(x, y) \) executes differentiation along the vertical direction \( Y \) (top-down) [5]:
As a result of the cyclic convolution (4) the twain of border segments (the upper and lower) is specified for each track, and the brightest of them is used for further analysis. The next stage involves the procedure of the track "thinning" for each track. The graphical scheme of this procedure is shown in figure 3.

\[
D_y(x, y) = \begin{bmatrix}
-1 & -2 & -1 \\
0 & 0 & 0 \\
+1 & +2 & +1
\end{bmatrix} \ast F_G(x, y) .
\]

(4)

Figure 3. Graphical scheme of the procedure of the track "thinning": by means of fatty borders the pixels that define the result of the thinning procedure are marked.

The grayed cells denote the pixels before applying the operation of track thinning (figure 3). The numbers in the cells (figure3) are the values of the derivative of the luminance in the pixel image. Namely, the pixels of the resultant thinner track line correspond to local maximums along the direction \(Y\) for each \(x\)-coordinate of the previous track line.

The double threshold filtering of image \(D_y(x, y)\) by means of the first and second threshold constants is executed at the next stage. The first threshold level of partial derivative is determined as product of the first constant 0.1 by the maximum value of partial derivative. The second threshold level of partial derivative is determined as product of the second constant 0.2 by the maximum value of partial derivative. If the partial derivative for current pixel is greater than the second threshold level of partial derivative, then the pixel is considered to be reliable. The pixel is removed if its partial derivative is less than the first threshold level of partial derivative or it is between the first and the second threshold levels and there is no reliable pixel in the neighborhood. All above mentioned stages of processing of image were executed, and respective result is shown in figure 4.

Figure 4. The results of the particle track separation procedure (which depicted in figure 2).

Analyzing the processed tracks set, the areas of discontinuities of some tracks, divided into pairs of "adjacent short" tracks, are determined. Then such pairs of "adjacent short" tracks are smooth joined together into "solid" tracks (restoration of discontinuous tracks). At the next stage, in the final set of processed tracks determines those tracks whose lengths with respect to the average length are estimated as “outliers”. The outliers - tracks are excluded from further consideration. The results of such procedure for processing tracks are shown in figure 5.
Figure 5. The procedure results of smooth joining of particle tracks and “outliers” estimation: 
(a) some tracks before processing; (b) processed tracks.

At the final stage, the length of tracks is computed in accordance with the Hough transform method [6]. Then the velocity of particles, which have the residual tracks in the image, is computed in accordance with equation (1). Figure 6 shows the computed distribution of particle velocity along the axis of the plasma jet according to distance measured from the muzzle of the plasmatron.

Figure 6. The calculated distribution of particle velocity along the axis of the plasma jet according vs. distance, measured from the plasmatron muzzle.

As can be seen in figure 6, the initial section of the plasma jet detects a weak trend of particle velocity growth, and at the particle velocity is stabilized at a distance of about 35 mm from the plasmatron muzzle. A very short time of the frame exposure (must be set before recording) allows to obtain the images, in which the track lengths is very small, and these tracks look like the bright pixels associated with the particle images (figure 7).

Figure 7. The optical image of the particle flux recorded by a high-speed digital camera (exposure time of frame is 2 μs).

Each frame, which is similar to the image in figure 7, allows one to determine the distribution of the particle density depending on x-coordinate along the axis of the plasma jet (figure 8).
Figure 8. The computed distribution of the particle density vs. x-coordinate along the axis of the plasma jet.

It means that the particle density, corresponding to x-coordinate, is a percentage content of the particle fraction which are concentrated in a small cross section of thickness Δx, and the center of the cross section of particle flux along the jet axis corresponds to the x-coordinate. The essence of the algorithm, by which was computed the distribution diagram (it is shown in figure 8), is quite simple and is as follows. For each x-coordinate (along the jet axis), the brightness of image pixels along the transverse direction Y is summed and then this sum is normalized by the total brightness of all image pixels.

The particle density tends to decrease with increasing of distance from the plasmatron muzzle: it is due to the presence of the opening angle of the jet, whereby the bulk density of the particles decreases (figure 8). The diagram depicts the "alternation" of sections of compaction and decompaction, which emphasize the wave dynamics in the longitudinal direction of the jet. Figure 9 reflects the image frame with an exposure time of 10 μs, which was used to determine the directions of the velocity vectors of the particles relative to the stream axis [7].

Figure 9. The optical image of the particle flux recorded by means of the high-speed digital camera (exposure time frame of 10 μs).

In figure 10 the diagram shows a dependence of differential density distribution of particles vs. orientation angle α of their tracks directions relative to the flux axis (for the cross-section with width S at the end of the jet before the target, figure 9). In other words, angle α is the deflection angle of the velocity vector of the particles from the direction of normal leakage onto the target.

In figure 10 the percentage of particles with deflection angle α of track directions is defined as the ratio of the number of particles with deflection angle α of track direction to the total number of particles (in the volume of the cross-section at the end of the jet).
Figure 10. The dependence of differential density distribution of particles vs. orientation angle of their tracks directions relative to flux axis (for the cross-section at the end of the jet before the target).

As can be seen from the diagram (figure 10), most of the particles (in the cross section of the plasma jet before the target) move in the direction of the normal onto the target coinciding with the flux axis. When the deflection angle relative to the flux axis increases (as anticlockwise so and clockwise), the percentage of particles drops sharply. In other words, in accordance with the technology requirements of the spraying of coatings on the machine parts the particle flux becomes laminar substantially before the target at the end of the jet.

3. Conclusion
As a result of images processing in the various cross-sections of the plasma spraying jet can be calculated the dependences of differential density distribution of particles vs. orientation angle of their tracks directions relative to the flux axis. Such dependence makes it possible to estimate the extent of laminarity of plasma jet, which plays an important role in the coating spraying technology.

The application of methods of processing images, obtained by modern high-speed video cameras, allows you to explore the complex dynamics of heterogeneous fluxes of particles during the plasma spraying of coatings on the machine parts. The results of these studies are of interest for solving the optimization problem for gas-thermal technologies, including the technology of plasma spraying of functional coatings.

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