Three dimensional optical imaging of irregularly shaped plasma jets

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Abstract. This communication presents an algorithm for reconstructing the 3D distribution of optical radiation from a plasma object of irregular shape. The object is seen by a camera at three different angles. The photo density profiles in each single line of the three images are presented as sums of Gaussians; the reconstruction is made by means of a set of equations that relate radiation intensity in a 2D mesh to the Gaussian amplitudes. An example based on photographs of a typical plasma jet used for atmospheric plasma spraying is worked out.

1. Introduction
The shape and structure of complex plasma objects has successfully been studied by tomography [1]. This methodology requires acquisition and processing of a large amount of data. Here, we report the use of three optical images obtained simultaneously from different angles to reconstruct the spatial distribution of the radiation power density (RPD) from a plasma jet produced by an arc torch. If the jet is nearly axi-symmetrical, the problem can be solved by approximating the emission distribution within each jet cross section by a Gaussian [2]. Here, jets of more irregular structure are studied the RPD being represented as a sum of Gaussians. (There have been reports on multi-aspect imaging techniques used in other fields such as medicine, e.g. [3].)

2. Geometrical model of the jet
The plasma jet issued from the nozzle of an arc torch propagates (figure 1) along the line AA'. Here A is the center of the nozzle outlet. Light is intensively radiated from a zone (jet core) bounded by the contour line BB'A'D'D (jet boundary). Every cross section of this zone is of elliptical [2] or more complex shape described by parameters $Z_i$, $i=1,2,\ldots,N$, that are functions of the axial distance $z = AO$ and time $t$. Let $P$ be the radiation power density (RPD). The quantity that is experimentally measured is the radiant exitance which for optically thin radiator is given by

$$I(x,z,t) = \int P(x,y,z,t) \, dy,$$

for an observer with line of sight parallel to y-axis (figure 1).

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3. **Light emission distribution and reconstruction algorithm**

For any fixed value of $z$ and $t$, the radiant exitance from a thin layer enclosing the corresponding cross-section (figure 1) is distributed along $x$ as $I(x)$, which is approximated by a sum of $2n+1$ Gaussians (Gabor type transform [4]),

$$I(x) = \sum_{i=-n}^{n} A_i \exp\left[ -\frac{1}{2} \left( \frac{x - iB_0}{B_1} \right)^2 \right]. \quad (2)$$

Here $A_i$ are amplitudes, $B_1$ semi-width and $iB_0 (-n \leq i \geq n)$ displacements of Gaussians relative to the point $x = 0$.

In this paper we propose a technique to find RPD from measured values of the radiant exitance, see equation (1). Thereupon the aim of our reconstruction is to identify the jet boundary by setting this at a fixed value (e.g. $1/e$ of maximum) in the experimentally measured radiant exitance profile. Figure 3 shows such a profile fitted by (2) with $n=3$.

Our experimental set up is shown in figure 2. A single imaging device – a fast CCD video camera – views the jet via three mirrors positioned so that three aspects, at $45^\circ$ from one another, are obtained. Firstly, a sequence of triple images of the jet is taken (e.g. see multimedia enhancement *Sequence of Images M*). Each photograph is then used to make a three-dimensional reconstruction of the jet shape (e.g. figure 5) as follows (see also the multimedia enhancement *figure 4M*):

(I) For several (e.g. about 10 to 20) axial positions along the jet, $z = \text{const}$, the cross-sectional plane is divided into a number of cells (e.g. in figure 4: $6 \times 6$ cells); the “reconstructed” RPD values at cell centers are denoted $Z_1, Z_2, \ldots, Z_m$.

(II) For each axial position the photographic density, known also as pixel value, is measured at a number of points along the $x$-axis, within each of the three images;

(III) The pixel values obtained, for each image, are approximated by a sum of Gaussians (2);

(IV) From the amplitudes $A_i$ (2) the values of $Z_i$ are found (ill-posed problem) by solving a set of equations which in the case of figure 4 takes the form
\[ A_1 = Z_1, A_2 = Z_2 + Z_4 + Z_7, \ldots, A_6 = Z_3 + Z_6 + Z_{10}, \ldots, \]
\[ A_{10} = Z_1 + Z_2 + Z_3, \ldots, A_{13} = Z_{11} + Z_{12} + Z_{13} \]
(3)

(V) If the number of equations (as in other cases) does not match the number of unknowns, a suitable minimization procedure is used;

(VI) Knowing \( Z_i \), the lines of constant RPD, including the jet boundary defined above, are drawn.

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Figure 3. Traverse scanning of a jet image and its Gabor transform (n=3). Horizontal axis: position in pixel, vertical axis: radiant exitance (pixel value) 8 bit digitized.

Figure 4. Example of image processing.

Figure 5. 3D reconstruction of a plasma jet; a) original image; b) reconstructed image.
4. Example of reconstructed plasma jet shapes

Our DC plasma torch was operated at a power of about 40 kW with air as plasma forming gas, and powder injection that caused severe asymmetry of the plasma flow. The jet was filmed with framing rate of about 1 frame/s and exposure time of about 1 ms. Significant differences in the jet position, dimensions and luminosity were observed from frame to frame (e.g. see multimedia enhancement Sequence of Images M). An example of 3D reconstruction for frame # 5 (t=const) is shown in figure 5. The multimedia enhancement figure 5M presents different aspects (angles of view) of the 3D reconstruction.

5. Conclusions

Such 3D reconstructions can be used to estimate, on-line, features of plasma geometry. In the case of plasma spraying, asymmetric propagation of the jet may influence the process of powder particles entrainment and heating. Jet asymmetry may also serve as an indicator of excessive nozzle erosion that precedes torch failure.

References

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