Multi-viewpoint imaging based simulations of sensors for APS jet monitoring

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Abstract. Test results are presented for different configurations of newly developed optical sensors consisting of several narrow-collimated photo detectors pointed at a plasma jet along different directions in its cross section. The sensors are capable of detecting time-variations of the position, width and asymmetry of a plasma jet. Two plasma torches with different plasma forming gas, air and argon/water vapor mixture, were used in our experiments under typical atmospheric plasma spraying (APS) conditions. The tests are based on fast, side-on imaging of the plasma jet from two or three angles (viewpoints). Reference values for the jet center coordinates, width and maximum brightness were deduced by processing the full information in the images. Next, data from small areas were processed to obtain values of the same parameters that simulate the sensor actual performance. It is commented that the accuracy of the new sensors seems reasonable for the purpose of on-line control of APS.

1. Introduction

In a number of thermal plasma technological processes, geometrical properties of the plasma jet such as position, width and asymmetry can strongly influence the quality of the end product. In the atmospheric plasma spraying (APS) \cite{1}, powder particles with 10 to 100 μm diameters are injected into a thermal plasma jet, subsequently melted and then deposited to a surface to form coatings of 100 μm to a few millimeters thickness. Such coatings have specific functional properties that are of interest for a wide range of applications, from wear and corrosion protection to biocompatible materials and solid oxide fuel cells.

Our publications \cite{2 – 5} describe simple optical sensors of geometrical properties: three to six narrow-collimated photo detectors (PD) are pointed at the radiating plasma object along different directions within a cross section of the object (plus one wide-angle PD in some cases). It is essential that different sensor configurations undergo extensive testing under conditions as close as possible to real situations in APS, as all geometrical and physical properties of the jet are strongly influenced by (i) plasma torch characteristics such as nozzle outlet diameter, (ii) torch regime – electric power and gas flow rate, (iii) operational drift and fluctuations inherent to the plasma torch, (iv) injection of powder particles.
An efficient way to do such tests is to use fast, side-on imaging of the plasma jet, then select small areas of the images that correspond to portions of the jet which will eventually be “seen” by the individual PDs. The photographic density within such areas simulates the PD signals. After appropriate calculations that simulate signal processing in the real case, the jet center coordinates and width are found within the chosen cross section of the jet. To simulate different orientation of the individual detectors, the plasma was imaged via a system of mirrors thus taking photographs at two or three different angles (aspects).

Two plasma torches with different plasma forming gas, air and argon/water vapor mixture, are used in the experiments under typical APS conditions. Reference values for the geometrical parameters are obtained by processing the full information in the images. Next, data from small areas are processed to obtained simulated values for the same parameters.

2. Principles of the new sensors

The measurements are based upon optical observation by several photo detectors (PD) pointed at the radiating plasma object (RPO) along three different directions in a plane cross section of the RPO. All PDs have identical spectral response. For our purposes, a certain type of light emission spatial distribution within the RPO is assumed. The characteristics of such a distribution are directly related to the RPO geometrical properties. Further, we describe how the PD output signals can be utilized to determine the geometrical properties by an appropriate signal fusion algorithm.

The PDs receive light each via a narrow pipe which restricts the field of view practically to a line of sight. A number of such lines are arranged in the jet cross-sectional plane with co-ordinate system Oxy, figure 1a. (Ideally, the cross section would be a circle with a centre at the origin O.) Let \( \theta_i \) be the angle of the \( i \)-th line \((i=1,2,\ldots,N)\) with the x-axis and \( r_i' \) the distance of the line to the jet cross-section center, C. It is assumed that

i. the jet cross-section is an ellipse, figure 1b, with semi-axes \( \xi, \eta \) at an angle \( \chi \) with the x-axis;

ii. the radiation leaving the jet, \( I_k \), is described by the Gaussian

\[
I_k = I_m \exp\left(-r_k'^2/R_k^2\right), \quad k = 1, 2, \ldots, N,
\]

where \( I_m \) is the signal when the PD is pointed at the jet cross-section center, \( R_k \) is the jet radius as “seen” by the \( k \)-th PD. For a special orientation of PD \( R_k=\xi \) or \( R_k=\eta \) it was found that experimental data on radial brightness distribution correlate with the predictions of equation (1), with correlation coefficient of about or greater than 0.95 [2, 3].

![Figure 1a. Radiating plasma object (RPO) and photo detectors (PD).](image1a)

![Figure 1b. Elliptical cross section of RPO.](image1b)

![Figure 2. Torch A (aspects 1, 2), torch B (aspects 1,2,3).](image2)

Let the origin of xy-coordinates coincide with the time-averaged position of the center, C, its instantaneous position being at coordinates \( x_c, y_c \).

Thus we have defined five geometrical properties of the jet cross section: \( x_c, y_c \) (characterizing position), \( \xi, \eta, \chi \) (characterizing size and shape). These quantities are related to the PD signals in a
Several types of sensors with 3 to 6 narrow-angle PDs are arranged so as to “see” the object from 2 or 3 angles (aspects). Table 1 shows a schematic outline of the sensors to be studied here and the formulae used to compute the RPO geometrical parameters:

\[ x_c, \ y_c, \ \chi, \ \rho = \frac{\chi + \eta}{2} \cdot 1, \ \varepsilon = \frac{\chi - \eta}{2} \]  

(2)

\[ I_k, I_k', \text{ and } I_k'' \] are PD output signals. One wide-angle PD with output \( I_4 \) is included in Sensor IV.

### Table 1. Sensors.

| Sensor I: 6 PD | Configuration | Formulae for calculations of geometrical parameters |
|---------------|---------------|--------------------------------------------------|
| 3 aspects;    |               | \( x_c = \frac{1}{4}(I_1' - I_1), \ y_c = \frac{1}{4}(I_2' - I_2), \) |
|               |               | \( \omega + 1 = \frac{1}{4}(I_1 + I_1' + I_2 + I_2'), \ \rho = \omega/3 \) |
|               |               | \( \mu = \frac{1}{4}(I_1 + I_1') - (I_2 + I_2'), \ \nu = \frac{1}{2} (I_3 + I_3') - (\omega + 1) \) |
|               |               | \( \chi = \frac{1}{2}\tan^{-1}(\sqrt{\mu}), \ \varepsilon = \mu/\cos(2\chi) \) |

(see [3])

| Sensor II: 4 PD | Configuration | Formulae for calculations of geometrical parameters |
|-----------------|---------------|--------------------------------------------------|
| 2 aspects       |               | \( x_c, \ y_c, \ \rho \) |
|                 |               | \( \chi = 0, \ \varepsilon = \mu \) |

(7)

| Sensor III: 6 PD | Configuration | Formulae for calculations of geometrical parameters |
|------------------|---------------|--------------------------------------------------|
| 2 aspects        |               | \( \psi_1 = [\ln(I_1/I_1'')/\ln(I_1'/I_1'')], \ \psi_2 = [\ln(I_2/I_2'')/\ln(I_2'/I_2'')] \) |
|                  |               | \( x_c = (\psi_1 + 1)/(\psi_1 - 1), \ y_c = (\psi_2 + 1)/(\psi_2 - 1) \) |
|                  |               | \( \eta = (1 + \xi)/(1 - \xi), \ \xi = (\ln(I_1'/I_1'') - \ln(I_2'/I_2''))^{1/2} \) |
|                  |               | \( \chi = 0, \ \varepsilon = \eta \cdot (1 + \rho), \ \rho = (1 + \rho) - \xi \) |

(see appendix)

| Sensor IV: 3 (+1 wide angle) PD | Configuration | Formulae for calculations of geometrical parameters |
|---------------------------------|---------------|--------------------------------------------------|
| 3 aspects;                      |               | \( W = I_4/[(\pi/2)^2/4], \ \rho = W/2^{3/2} - 1 \) |
|                                 |               | \( X = W(1 - \varepsilon^{1/2}), \ Y = W(1 - \varepsilon^{1/2}) \) |
|                                 |               | \( x_c = X - 1, \ y_c = Y - 1 \) |
|                                 |               | \( \chi = 0, \ \varepsilon = 0 \) |

(see [5])

### 4. Results and discussion

Experiments were carried out using free jets produced by two APS torches, a water-stabilized arc torch [6] (torch A) operated at power 100 kW and a wall-stabilized arc torch [7] (torch B) at 40 kW, with steam-argon mixture and air as a plasma-forming gas, correspondingly. Numerical simulations of sensors I to IV, table 1, were carried out using sequences of images filmed by fast CCD cameras from two (torch A) and three (torch B) aspects as shown in figure 2. Experimental and data processing details for some torch/sensor combinations have been reported elsewhere [2, 3, 5].

Tables 2 to 4 present typical results of simulation. Reference data are provided directly from the gaussian fits of photographic density obtained by scanning cross sections of the images, see multimedia enhancement Sequence of image M. Selected pixels from the scans simulate PD signals. The equations of table 1 are used to find the simulated values of the geometrical parameters.
### Table 2. Comparison of sensor performance for displacement measurements.

| Torch, image# | Simulated parameter | Reference value | Values from simulation of sensor operation |
|---------------|---------------------|----------------|-------------------------------------------|
| A 19          | $x_c$               | 0.161          | *                                         |
|               | $y_c$               | -0.083         | 0.237                                     |
|               |                     |                | 0.153                                     |
|               |                     |                | 0.236                                     |
| B 91          | $x_c$               | -0.075         | -1.00                                     |
|               | $y_c$               | -0.044         | **B 0.200**                               |
|               |                     |                | **B 0.200**                               |
|               |                     |                | **B 0.204**                               |
|               |                     |                | -0.077                                    |
| B 94          | $x_c$               | 0.005          | -0.027                                    |
|               | $y_c$               | -0.168         | -0.245                                    |
|               |                     |                | -0.179                                    |
|               |                     |                | -0.135                                    |
| B 112         | $x_c$               | 0.279          | 0.191                                     |
|               | $y_c$               | 0.017          | 0.112                                     |
|               |                     |                | 0.112                                     |
|               |                     |                | 0.076                                     |
|               |                     |                | -0.010                                    |

### Table 3. Comparison of sensor performance for width measurements.

| Torch, image# | Simulated parameter | Reference value | Values from simulation of sensor operation  |
|---------------|---------------------|----------------|-------------------------------------------|
| A 19          | $\rho$              | 0.009          | *                                         |
|               |                     |                | 0.015                                     |
|               |                     |                | 0.046                                     |
|               |                     |                | -0.013                                    |
| 91            | $\rho$              | -0.139         | -0.092                                    |
|               |                     |                | -0.083                                    |
|               |                     |                | -0.142                                    |
|               |                     |                | -0.184                                    |
| B 94          | $\rho$              | 0.102          | -0.046                                    |
|               |                     |                | -0.026                                    |
|               |                     |                | 0.228                                     |
|               |                     |                | **B 0.160**                               |
| 112           | $\rho$              | -0.052         | -0.058                                    |
|               |                     |                | -0.026                                    |
|               |                     |                | 0.058                                     |
|               |                     |                | -0.116                                    |

### Table 4. Comparison of sensor performance for ellipticity measurements.

| Torch, image# | Simulated parameter | Reference value | Values from simulation of sensor operation  |
|---------------|---------------------|----------------|-------------------------------------------|
| A 19          | $\varepsilon$       | -0.144         | *                                         |
|               | $\chi$              | -36.6°         | -28.2°                                    |
|               |                     |                | *                                         |
|               |                     |                | *                                         |
| 91            | $\varepsilon$       | 0.090          | 0.090                                     |
|               | $\chi$              | -22.2°         | -21.1°                                    |
|               |                     |                | *                                         |
|               |                     |                | *                                         |
| B 94          | $\varepsilon$       | 0.387          | **B 0.181**                               |
|               | $\chi$              | -23.7°         | -39.2°                                    |
|               |                     |                | *                                         |
|               |                     |                | *                                         |
| 112           | $\varepsilon$       | 0.169          | 0.194                                     |
|               | $\chi$              | -36.7°         | 0.142                                     |
|               |                     |                | *                                         |
|               |                     |                | *                                         |

As $x_c$, $y_c$, $\rho$, $\varepsilon$ are normalized to the time averaged jet radius, accuracy of about 0.1 seems reasonable for providing feedback in on-line automatic control. Except for a few cases, the simulated values for the linear parameters differ from the reference by less than 0.1, and for the angle $\chi$ by less than 10°. In tables 2 to 4, cases of greater difference are shown by bold lettering. Preliminary analysis of such cases shows that

i. Excessive inaccuracy is possible, if the signal is so low that error in digitizing takes place (illustrated by #91: $I_t=6$ with full range 0 to 255 for 8 bit processing);

ii. Exaggerated value for radius $\rho$ (#94) is probably due to concentration of directions of observation (figure 2) along the longer semi-axis of the ellipse;

iii. Excessive errors in ellipticity $\varepsilon$ are possible, if $\varepsilon \sim 0.5$ (illustrated by #94).
5. Conclusions

Some general trends are obvious. Complex sensor configurations such as I (table 1) are not always more accurate than simpler ones, unless information on the angle $\chi$ is needed. Whenever certain type of asymmetry is expected e.g. due to specific arc electrode behavior or powder injection, simple configurations such as IV may serve the purpose of automatic control, and strategic orientation of the lines of observation may also help. Studies of such trends are under way.

The accuracy of the new sensors seems reasonable for the purpose of on-line control of APS.

Appendix: the 6 PD, 2 aspect sensor

The derivation of formulae for sensor III, table 1, follows.

As detectors PD1" and PD2" are pointed at the RPO central zone, their outputs are, approximately, $I_1" = I_{1m}$ and $I_2" = I_{2m}$. Equation (1), for detectors PD1, PD1', PD2 and PD2', then becomes

$$\ln \left(\frac{I_1}{I_1''}\right) = -\frac{(1+x_c)^2}{\zeta^2} \quad \text{(A1)}$$
$$\ln \left(\frac{I_1'}{I_1''}\right) = -\frac{(1-x_c)^2}{\zeta^2} \quad \text{(A2)}$$
$$\ln \left(\frac{I_2}{I_2''}\right) = -\frac{(1+y_c)^2}{\eta^2} \quad \text{(A3)}$$
$$\ln \left(\frac{I_2'}{I_2''}\right) = -\frac{(1-y_c)^2}{\eta^2} \quad \text{(A4)}$$

where $\zeta$ and $\eta$ are defined in figure 1b by assuming $\chi = 0$, equation (11). Equation (A1) is divided by equation (A2), and (A3) by (A4). This yields

$$\left[\ln \left(\frac{I_1'/I_1''}{I_1/I_1''}\right)\right]^{1/2} = \frac{(1+x_c)/(-x_c)}{\sqrt{(1+x_c)/(-x_c)}} \quad \text{(A5)}$$

and, similarly, for PD2 and PD2'. Left hand sides are then denoted $\psi_1$ and $\psi_2$, see equation (8). It now remains to solve the resulting equations for $x_c$ and $y_c$, thus obtaining formulae (9). Back to equations (A1) to (A4), $\zeta$ and $\eta$ can be expressed in terms of PD signals as well as $x_c$ and $y_c$, equation (10). Equation (11) relates $\zeta$ and $\eta$ to ellipticity $e$, the radius $\rho$ being defined by equation (2).

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