Plasma airflow jets diagnosis by means of time-resolved tomography

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Abstract. A simple optical arrangement combining a single high-speed CCD camera and a set of mirrors has been setup to record simultaneously light intensity of atmospheric air plasma jet issued from multiple directions. The adopted approach is presented and its potential benefit to examine plasma emission in 3D is outlined. Rebuild local emission distributions are briefly analyzed for two typical jet exhibiting different flow structures.

1. Introduction
Thermal plasma jets produced at atmospheric pressure are extensively used in a wide range of industrial applications necessitating high energy density medium or elevated thermal fluxes. Additionally to the inherent interactions between the hot jet submerged into quiescent surrounding gas [1],[2] (mixing, entrainment, transition), the technology adopted to warm up the working gaseous mixture can be a stringent source of undesirable plasma flow jet spatial and temporal disturbances potentially detrimental to thermal processing quality [3],[4]. The examination of the plasma jet dynamic can be easily performed by means of high speed imaging measurement techniques. Various processing can be applied to plasma intensity, recorded with a high speed CCD camera for example, to uncover underlying jet dynamic characteristics [5],[6],[7],[8]. Nevertheless, recorded intensity corresponds to the optical emission integrated along the optical path (in first approximation parallel to the camera viewing direction) therefore fine interpretation of plasma jet dynamics taking place locally is limited, and obviously local emission can no more be rebuilt with the classical Abel transform, applicable only to symmetric emission profile.

Tomography technique can provide a deeper understanding of the plasma jet temporal behavior, when analysis of line of sight measurements is no more sufficient, since tomography-based techniques are especially dedicated to rebuilt the local emission from intensity recorded at various directions. If tomography technique has already been used in the past to document thermal plasma jet local emission distribution [9], the present contribution addresses the development of tomography based technique using a single CCD camera. The new diagnostic method has been applied to the investigation of air plasma jets produced with a Microwave Plasma Torch (MPT). Principles of tomography and the numerical method adopted to rebuild
local emission from experimental intensity profiles are described in Section 2. The experimental arrangement presented in Section 3 combines a single CCD camera with mirrors to produce simultaneous intensity records as if they were obtained with a setup of 5 CCD cameras. The rebuilt 3D emission distributions are shortly analyzed in Section 4 for two typical cases of plasma jets.

2. Local emission reconstruction method
Considering a two dimensional plasma medium of finite extent in the plane \((x, y)\) and centered on the origin \(O\) as depicted in figure 1, the tomography technique consists in the reconstruction of the local emission distribution, referred as \(J(x, y)\), starting from its orthogonal projection on plane perpendicular to direction passing by \(O\) and making an angle \(\theta\) with \(x\)-axis. The line-of-sight intensity profile \(I(x', \theta)\) corresponds to the plasma radiation integrated along optical path parallel to the viewing direction specified by \(\theta\). Knowing \(J(x, y)\), projections at any angle \(\theta\) are obtained by mean of Radon transform and reciprocally, the local emission distribution is reconstructed applying inverse Radon transform to side-on intensity profiles, known in practice for a limited number \(K\) of viewing directions.

![Figure 1. Tomography principle.](image)

In the present study, the local emission distribution \(J(x, y)\) is reconstructed adopting the approach described in [9], based on the iradon function under MATLAB environment to calculate the inverse Radon transform starting from \(K\) experimental intensity profiles recorded at equidistant angle. Assuming the plasma is optically thin, the intensity profiles recorded at two opposite directions are mutually flipped, reducing then the useful domain of angular scanning from \([0 − 2\pi]\) to \([0 − \pi]\). The approach consists in the generation of additional intensity profiles by means of trigonometric interpolation to extend the initial set of \(K\) measured profiles to enhance reconstruction procedure quality. Considering that profiles at any projection angle \(\theta\) can be approximated by polynomials as \(I(x, \theta) = \sum c_n(\theta)x^n\), polynomial coefficient are
determined for $\theta_k = \frac{\pi(k-1)}{K}$, $k = 1, 2, ..., K$, by means of common least square fitting applied to recorded data. Also considering that $c_p(\theta)$ coefficients are smooth $2\pi$-periodic functions, coefficients at intermediate angle $\theta_k + \frac{\theta_{k+1} - \theta_k}{2}$ can be expressed analytically for fast evaluation [9]. Such procedure leads to double the number of available intensity profiles, henceforth well determined at $\theta_k = \frac{\pi(k-1)}{2K}$, $k = 1, 2, ..., 2K$. Repeating the procedure $P$ times with an initial set of $K$ experimental profiles results in a set of intensity profiles determined for $\theta_k = \frac{\pi(k-1)}{2^P K}$, $k = 1, 2, ..., 2^P K$.

The effective enhancement when interpolated profiles are taken into account into the rebuilding procedure has been assessed in [9] through qualitative comparisons between a reference distribution $J^{ref}$ and the distribution $J^{sim}$ reconstructed with iradon applied to intensity profiles computed for $K = 4$ initial projection angles. The improvement with increasing numbers of input profiles was quantitatively estimated evaluating the Root Mean Square Error (RMSE) between a reference emission distribution $J^{ref}$ and the distribution $J^{sim}(K, P)$ rebuilt using an initial set of $K$ intensity profiles and doubling $P$ times the initial set. Two synthetic emission distributions have been used to test the performance of the tomographic reconstruction. We have generated these planar distributions to be representative of the situations observed afterwards: a replete distribution and a hollow distribution that discloses intensity drop in the central region with irregular frontiers. The effect of the interpolated intensity profiles on the accuracy and quality of the rebuilt emission is clearly depicted in figure 2. From each reference distribution, $K = 5$ initial profiles have been obtained by means of the direct radon transform (from practical point of view, as if $K$ detectors were disposed to record the intensity along $\{\theta_k\}$ directions, indicated with inserted white arrows). Then this initial set is processed with the inverse radon transform to rebuild the emission distribution. For both type of situation, the emission distribution rebuilt with $K = 5$ initial profiles ($P = 0$) exhibit a poor quality and are characterized by a significant numerical noise and artifacts. By extending the initial set of profiles, presently by doubling two times ($P = 2$) the quality is substantially enhanced the noise is significantly reduced at the expenses of sharp contours smoothing, accordingly to the trigonometric interpolation method.

Unlike classical tomography, the single CCD tomography technique presented in this paper involves a relationship between the spatial resolution and the number of intensity profiles taken into account. We evaluate the effect of the spatial resolution decay with increasing $K$, as constrained with arrangement combining a single linear detector array with $K - 1$ mirrors (analogous to the setup described in Section 3 for $K = 5$). With such arrangement, when $K$ profiles are recorded with a detector of $N_{pix}$ pixel array size, $N_{pix}/K$ pixels are available to record a distinct intensity profile. The effect on the rebuilding procedure with increasing $K$ is evaluated, for initial array size set to $N_{pix} = 800$ pixels, calculating the RMSE between a reference emission distribution $J^{ref}$ and the distribution $J^{sim}(K)$ rebuilt with an initial set of $K$ intensity profiles: $RMSE(K) = \frac{1}{N} \times \sqrt{\sum_{ij} (J^{ref} - J^{sim}(K))^2}$, with $J^{ref}$ discretized according to the intensity profile array size reduction with increasing $K$ as $N_{pix} = \frac{800}{K}$, $i$ and $j$ referring to pixel indexes. The effect of the spatial resolution diminution on the rebuilt data quality with increasing $K$ can be assessed in figure 3 for the two reference shapes, where distributions rebuilt for $K = 3, 5$ and 9 (and $P = 4$), are evinced with the reference distribution at finer spatial discretization. For $K = 3$, the insufficient number of sampling direction is responsible for shape symmetrization trends. For $K=1$ the rebuilt shape is perfectly symmetric. For $K = 9$, the shape is slightly altered, in comparison to the case $K = 5$, because of the too low spatial resolution. Especially, in the case of the hollow shape, the small jagged patterns at the center, still distinguishable for $K = 5$, are noticeably degraded and blurred for $K = 9$. RMSE values plotted in figure 4 show that increasing $K$ enhances the rebuilding procedure up to optimal $K$ (slightly varying with the reference distribution shape) after which rebuilt data quality is deteriorated following
on insufficient spatial resolution. These considerations substantiate the number of projection angles considered in the implemented arrangement.

**Figure 3.** (From left to right) Reference distribution $J^{ref}$, and distributions $J^{sim}(K)$ rebuilt with increasing $K$, $K = 3$, $K = 5$ and $K = 9$, resulting in spatial resolution lowering. The upper, resp. lower, image series refer to the replete, resp. hollow, distribution case.

### 3. Equivalent N-camera arrangement

Various detection systems can be envisaged to sample simultaneously side-on intensity profiles emitted in multiple directions by a horizontal slice of plasma jet flowing along the direction $z$.
perpendicular to \((x,y)\) plane. CCD high speed cameras are particularly well suited to provide, with simple arrangement, the required input data to rebuild, with the method exposed in Section 2, the temporal behavior of the local emission distribution \(J(x,y,z)\) in the whole plasma jet volume. If \(K\) cameras are available, then the required side-on intensity spatial distribution \(I(x',\theta_k,z)\), \(k = 1, \ldots, K\), can be straightforwardly acquired displaying the \(K\) cameras to record plasma intensity at \(K\) equidistant angles. Unfortunately, CCD high speed cameras remain still too expensive nowadays to easily access to more than one. To overcome the situation, an arrangement combing a single CCD camera with \(K - 1\) mirrors equivalent to \(K\) cameras setup is proposed. The arrangement is based on the simple idea that the direct front image of the plasma jet and additional images seen from the rear can be recorded simultaneously with a single CCD frame with the help of mirrors.

In the experiments presently reported, images are recorded with a Phantom v7.0 8 bit CCD camera, offering a large scale array of \(800 \times 600\) pixels conductive to obtain five distinct images of the vertical jet with reasonable spatial resolution. The experimental arrangement has been designed to investigate the air plasma jet produced with a Microwave Plasma Torch consisting basically of a wave launcher operating commonly at 2.45 GHz coupled to cylindrical quartz tube of \(30 \text{ mm} \) inner diameter, the air flow is injected by means of a swirl injector from the bottom tube. In the present experiments the air plasma jet is produced in room ambient air at atmospheric pressure and the plasma temperature is of \(5000 \text{ K}\). MPT properties have been detailed in previous contribution [8] and will be not repeated here. The CCD camera has been combined with four ordinary mirrors (20 cm length and 8 cm width) to record simultaneously side-on intensity spatial distributions \(I(x',\theta,z)\) issued from five co-planar directions perpendicular to \(z\)-axis. The arrangement design is sketched in figure 5. The camera was positioned with the CCD chip vertical (parallel to \(z\)-axis), and perpendicular to and centered on the \(y\)-axis defined as the horizontal straight line crossing \(z\)-axis at the origin \(O\) located at 4.3 cm above the outlet. The mirrors have been displayed to collect the intensity issued from viewing direction of angles set to \(\theta_k = \pi(k - 1)/K + \pi/\theta_1\), \(k = 1, 2, \ldots, K\), with \(K=5\). With the adopted disposition, the CCD central image corresponds to the plasma jet direct front view at projection angle \(\theta_8 = -\pi\) with \(I(x',\theta_3) = I(-x',\theta_8)\). The four mirrors have been oriented to conserve, after reflection, the optical path parallel to \(y\)-axis. To do so, the angles between a given sampling direction \(\theta_k\) and the normal to the mirror is set to \(\frac{1}{2}(\pi/\theta_1 - \theta_k)\). External mirrors (associated to sampling direction \(\theta_1\) and \(\theta_5\)), resp. internal mirrors (associated to sampling direction \(\theta_2\) and \(\theta_4\)), have been located at respective distance \(r_{ext} = 14.7 \text{ cm}\) and \(r_{int} = 11.9 \text{ cm}\) from \(z\)-axis to reduce width and depth covered by the arrangement in \(x\) and \(z\) directions (to minimize off-\(y\)-axis perspective distortions), letting however margin between adjacent images displayed on the frame. A common 35 mm lens NIKKOR-S was used to image the arrangement on the whole CCD frame, setting distance between camera lens and \(z\)-axis to 74 cm. The focus was adjusted.

![Figure 4. Evolution of the RMSE with increasing \(K\). The black, resp. red, curve refers to the hollow, resp. replete, distribution case.](image-url)
using a simple ruler displayed vertically with printed numbers coinciding with $z$-axis. The focus was finely tuned *de visu* by balancing the blurring effect, albeit only slightly perceptible, to obtain for all viewing direction sharpest numbers. A typical raw CCD frame acquired for the reference case is shown in figure 6. The central image corresponds to the plasma direct view, the two images adjacent on the right and left to central image correspond to the rear plasma jet intensity reflected by internal mirrors and the two images on the edges of the frame correspond to rear intensity reflected by external mirrors.

Figure 5. Top view drawing of the optical arrangement with four mirrors.

Since images are issued from apparent plasma jet at different location (especially at different depth), the intensity distributions imaged onto the CCD can be significantly distorted because of the actual perspective projections. Checkerboard images analysis with Camera Calibration Matlab tool box evinced that the distortion of images in the region of interest for the processing is negligible. The main effect of the perspective projection is the shortening of the images clearly visible in figure 6. Indeed, the images obtained for projection angles $\theta_k$, with $k=1, 2, 4$ and 5, corresponding in fact to reflected images, are actually issued from intensity going along optical path lengthened of $d_{ext/int}$ compared to the direct image with $d_{ext/int} = r_{ext/int}(1 + \sin(\theta_{ext/int}))$. It comes out that the apparent relative depth between the plasma jet viewed directly and viewed through mirrors is of $d_{ext} = 19.2$ cm and $d_{int} = 21.5$ cm. Therefore the plasma jet images obtained with mirrors exhibit a foreshortening in comparison to the direct front image following on the apparent size reduction with increasing depth inherent to perspective projection. We checked with the checkerboard that the rear plasma images collected by the CCD chip result as a good approximation from intensity following optical path parallel to direction specified by $\theta_k$ before reflection and parallel to $y$-axis after reflection. Therefore, we reasonably assumed in the followings that distortions undergone by intensity distributions are weak enough to do not deteriorate reconstructed data reliability. However, such an approximation could be refined with a proper image geometrical calibration or using telecentric lens.

The raw frame records have been processed to elaborate five distinct temporal frame series corresponding to records as if they were obtained with a five cameras arrangement. Neglecting off-axis effects, the five plasma jet image series have been corrected as if they were obtained by mean of an equivalent five camera arrangement with cameras placed at different distances from $z$-axis (74 cm, $74 + d_{ext}$ cm and $74 + d_{int}$ cm). Hence, corrections have consisted in scaling intensity distributions obtained for different depths. The scaling procedure was performed using
the plasma jet itself as reference source, considering that for long acquisition time the plasma jet emission distribution is axisymmetric following on plasma jet oscillations statistical averaging. A plasma jet generated with the MPT at 18 l/min of air, to guaranty a fairly stable jet, has been used as reference. A single frame record is given in figure 6. Mean intensity distributions, obtained averaging 1000 raw frames recorded at 140 Hz exhibit a very good symmetry along the whole jet axial extent as seen in figure 7. For each projection angle, the spatial resolution is determined on the basis of the tube diameter to specify the array size in pixel of a window defining a region of 6 cm width and 8.2 cm height. Each window is centered on the jet axis, determined as the maximum intensity line (coinciding with the vertical $z$-axis).

Then, these sub-frames are extracted and discretized on a common grid data point size to have set of five images compliant in spatial resolution and data array size. The intensity profiles are scaled to a reference value to obtain images calibrated in relative intensity. Extracted and scaled instantaneous frames are displayed in figure 8 for two plasma jet cases discussed in Section 4. Such data process applied to time series of recorded images allow to elaborate five distinct movies equivalent to movies as if they were obtained with five distinct CCD cameras spread to record intensity distributions at viewing directions of angles $\theta_k = \frac{\pi(k-1)}{K}, k = 1, 2, ..., K$, with $K = 5$. 

**Figure 6.** Single CCD frame recorded with the airflow plasma jet produced at 18 l/min.

**Figure 7.** Sub-frames extraction.
Figure 8. Five distinct frame series elaborated as input to tomography rebuilding procedure. Frames for $K = 1, ..., 5$ from right to left. First raw common plasma jet, second raw cyclonic plasma jet.

4. Results and discussion
Tomographic measurements have been performed with the MPT operating with air at two flowrates. In the following, a short analysis of the rebuilt emission distribution is proposed for two cases to outline the potential gain of the diagnostic. The first case (case:A) corresponds to a usual plasma jet case, it is produced at 46 l/min flowrate. The second case (case:B) corresponds to the plasma produced at 65 l/min exhibiting a cyclonic flow structure characterized by a pressure drop at jet center. For the two cases operating power of 2 kW was used and frames have been recorded with acquisition rate of 5 kHz with exposure time of 190 µs. The 3D distributions obtained using the approach described in Section 3 with the method outlined in Section 2, are examined hereafter for the so-called A and B cases. In the followings, resulting emission distributions are represented in two complementary manners to facilitate the appreciation of peculiarities taking place in the three space dimensions. Iso-emission envelops (i.e. $J(x,y,z) = constant$) are plotted for high, intermediate and low emission values, highlighting differences between hottest and coldest plasma regions. Horizontal cross sectional views at succeeding heights are shown together with iso-emission surface plots, to evince distribution characteristics in the plane $(x,y)$. The intersections between the section plane and the envelops is represented by black lines displayed on the sectional views.

Looking at the instantaneous distributions the plasma flow features exhibits outstanding peculiarities. For case:A, evinced in figure 9, the situation is closely consistent with common cylindrical hot jet submerged into a cold quiescent gas [1],[2] characterized by mixing interactions established at the jet frontiers (turbulent region) disclosing a dominant potential core region (laminar region) very analogous to combustion and isothermal jet. However, the cross sectional view shows that the region that can be related to the core potential at $z = 0$ and 2 cm is closer to an elliptic distribution indicating a torsion-like along $z$-axis. Initial outer layer disturbances observed at the plasma jet base show that the cold air entrainment process has started, probably triggered earlier than with non swirling flows because the swirl enhances the entrainment of surrounding air. Moving away from the outlet, the initial disturbances seem to turn into large eddies stepping toward the jet centerline. The gradual increases of the cold air engulfment rate results in the strangulation-like phenomena at about $z = 4$ cm where eddies of entrained surrounding cold air have finally reached the centerline, resulting afterward in a detachment process of the jet termination. For case:B, shown in figure 10, the cyclonic
structure takes place following on the pressure reverse breakdown occurring as a rule for high swirl numbers. The plasma flow exhibits an outstanding structure recalling in a certain extent a hot tongue that sweeps on the tube inner wall. The mean emission, obtained averaging a series of 500 instantaneous emission values, is reported to highlight the differences between the plasma emission seen at low acquisition rate (as seen by a human eye or an ordinary camera) and the actual dynamic features accessible at 5000 KHz acquisition rate. The resulting mean emission distributions are displayed in figure 11 for case:A and in figure 12 for case B. For case A, the thermal jet emission appears to be structured in quasi-conical concentric layers uncovering a mean temperature decreasing monotonically away from the center. For case:B, the pressure collapse is well distinguishable with both representations of the mean emission. The emission distribution displays a symmetric annular shape in contrary to the instantaneous emission distribution, indicating that the dynamic of the hottest region is totally averaged for long recording time. For both cases, a fair symmetrical distribution was obtained with emission integrated over $\sim 0.1$ s.

Having access to the 3 D distribution of local emission, new features, that are inaccessible by means of image analysis, can be obtained. We consider presently the cyclonic jet (case:B), which
Figure 11. Mean emission distribution for the common jet case (case:A). At left: cross sections of emission distribution in the plane \((x, y)\). At right: iso-emission layers.

Figure 12. Mean emission distribution for the cyclonic jet case (case:B). At left: cross sections of emission distribution in the plane \((x, y)\). At right: iso-emission layers.

is composed of a hot localized spot of plasma rotating in the plane transverse to the flow axis as depicted in the series of sectional views at the \(z = 0\). This series represent well the rotation of the plasma spot shown here with time increment of \(2.2 \times 10^{-3}\) s. The angular position of this plasma spot is obtained as the angle \(\theta\) defined by position of the maximum of the emission distribution with respect to \(x\)-axis. We consider first the temporal intensity collected through three distinct line-of-sight, namely following the direction parallel to \(y\)-axis and passing by \(x = 0\) (the center), at \(x = +1\) cm and \(x = -1\) cm. The time evolution of the extracted intensities (as it have been collected by an array of three detectors) is reported in the upper plot of figure 13 together with the time evolution of the angular position. The associated FFT to each of these temporal information has been reported on the lower plot. The intensity acquired at \(+/- 1\) cm is characterized by a well distinct period of about \(\sim 150\) Hz which is the period of the rotation of the plasma spot (period of \(\theta\)). While the intensity recorded at \(x = 0\) cm, is instead characterized by a frequency of twice the plasma rotation frequency (peak located at \(\sim 300\) Hz). This feature
is explained by the fact that during one period of rotation, the plasma spot is detected only once at \(x = \pm 1\) cm, while at \(x = 0\) the plasma spot is seen two times per period: passing at \(y \approx +1\) cm and at \(y \approx -1\) cm (for each \(x = 0\)). In other words, considering only image analysis is insufficient to interpret the features displayed by the time intensity measurements since it can lead to misinterpret the frequency analysis. Without additional information (or a priori assumption), the two peaks at \(\sim 150\) and \(\sim 300\) Hz tell that the plasma dynamics is driven by two distinct periods. Only the local emission distribution analysis can reveal the underlying nature of the plasma dynamics.

**Figure 13.** Left column: Sectional views of the plasma spot position at various instants. Right column: Time evolution of intensities and maximum emission angular position (upper plot). Associated FFT (lower plot)

5. Concluding remarks
A tomography approach based on a single CCD camera has been proposed to document the temporal behavior of the plasma jet local emission produced by a Microwave Plasma Torch. Assuming the plasma optical thin, the problem was abridged to the simultaneous sampling of radial intensity distributions issued from equidistant viewing directions in the range \([0 - \pi]\). Allowing subsequently to propose a simple arrangement to record with the same frame the intensity issued from various direction with the help of ordinary mirrors. The technique was applied to the tomographic analysis of two plasma jet case exhibiting distinguishable structure to assess the potentiality of the adopted approaches. Starting from the 3 dimensions emission distribution, significant insights can be brought with numerical processing commonly used to examine 2D images (temporal and spatial analysis). Preliminary results showed that the technique is promising and it is worthwhile to evaluate its application to wide range of plasma jet facilities.
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