VISUALIZATION OF FLUCTUATION OF RADIANT FLOW BY ENTROPY MAPS

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Abstract
A digital camera coupled with computer has great potential in analysis of flame and discharges structures. This work analyzes an approach to visualization of dynamic radiant flow. Mapping of brightness uncertainty values is used to show regions of different fluctuation intensity of the flow. Entropy as described by information theory was used as relevant parameter for uncertainty value. By mathematical procedure relative parameter was derived based on entropy. As result effect of optic sensitivity or imperfections of experimental set-up were significantly suppressed. Example of its utilization for plasma jet investigation is demonstrated. The method combines clearness, robustness and flexibility and can be effective tool for the basic characterization of the flows.

Introduction
Photographic images are often used as primary characterization of plasma jet [1,2] or flames [3,4]. Space distribution of brightness values gives an idea where more intensive processes take place. While fast shutter image can give information on momentary state of the processes general analysis needs treatment of representative number of images. Statistical processing is used for such characterization and proper parameter and method should be chosen. This paper is focused on analysis of statistical processing for visualization of such unstable parameter as plasma or flame brightness.

The method was developed to analyze plasma jet generated by dc arc plasma torch. Wide variety of plasma properties, ambient conditions and plasma processes issued a challenge and authors tried to meet requirements of usability, robustness and accuracy by one mathematic procedure. Physical interpretation of the result was also kept in mind and authors believe that the procedure with its flexibility and clearness can be very affective in characterisation of structure of flames, electrical discharges and other fluctuating objects.

Experimental techniques
In this paper thermal plasma jet was used as the test object. The jet was generated by a plasma torch with water-argon stabilization of arc WSP®H 2000 [5]. Torch schematic is shown in Fig.1. Plasma is generated in electric arc in argon-steam atmosphere. Argon is supplied along the cathode in the arc chamber and steam is generated from the inner walls of the water vortex. Resulting argon-hydrogen-oxygen plasma exits the torch through the nozzle. The anode is situated outside the torch under the plasma jet. A part of arc branches from the main plasma flow to attach the anode surface. The torch is known to generate very stable plasma flow near the nozzle, which however rapidly transfers to a mode of intensive turbulent mixing with ambient air. Besides hydrodynamic instabilities the arc-anode attachment is known to be strong source of plasma disturbances [6].

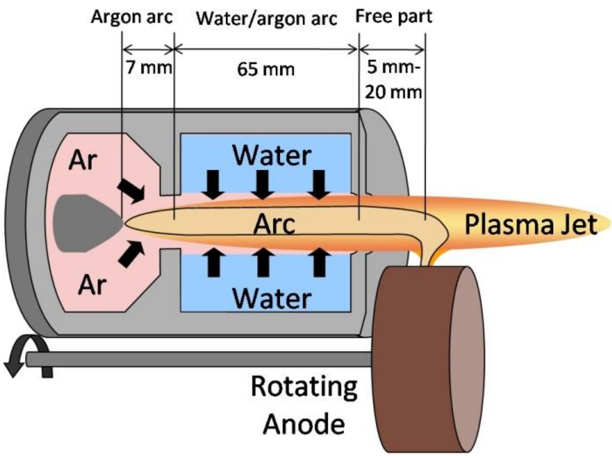

Figure 1. Schematics of thermal plasma torch with argon-water stabilization of arc.

CCD camera SensiCam Fast Shutter (by PCO AG) was used for plasma jet photographing. It was equipped with common lens Exacta 70-210 mm. A combination of aperture value and gray filter were used to avoid over-brightness. Exposure time of 3 μs was used to get momentary image of plasma. Sequence of at least 300 photographs was used for mathematic processing. Matlab program (by The MathWorks, Inc.) was used to realize the processing algorithm.

Requirements to processing algorithm

To characterize fluctuations experimental set-up and method should fit some needs in space and time resolution, accuracy and robustness. Processing evidently should be based on sufficiently big number of images. Exact number depends on object itself and can be defined based on previous experience supported by guidelines on sample determination [7]. The sequence should include fluctuation of different time and space scales. It defines required resolution of photograph and time scales. Time of taking photograph sequence should be longer than time of slowest fluctuation expected. In the same time exposure time should be shorter than the fastest expected fluctuations.

Brightness fluctuation amplitude depends on discharge fluctuation intensity and on the experimental set-up as well. Lower sensitive optics would provide lower brightness as it is shown in Fig.2 and lower brightness fluctuation for the equal objects. To suppress sensitivity effect either calibration to some reference object should be done or statistical parameter should have relative character.

Another issue is non-uniform distribution of light. Radiation of object can vary in large ranges in one image. Fig. 3. is photograph of expansion of plasma flow in case of supersonic speed. Density of plasma drops drastically when plasma escapes the nozzle. Lice in the case with different sensitivity of optics brightness fluctuation will be depends on the value of brightness in particular location. Normalization of brightness would very ambiguous in this case. Different regions of brightness should not interfere during the analysis and statistical processing should have local character. It is argument for relative character of statistical characterization when statistical parameter characterise rather shape of distribution than its scale.

It can be summarized so that the attention should be paid to have representative set of images in number, sequence record duration and exposure time; the processing should have local character and should provide relative value to suppress influence of total brightness in the processed area.

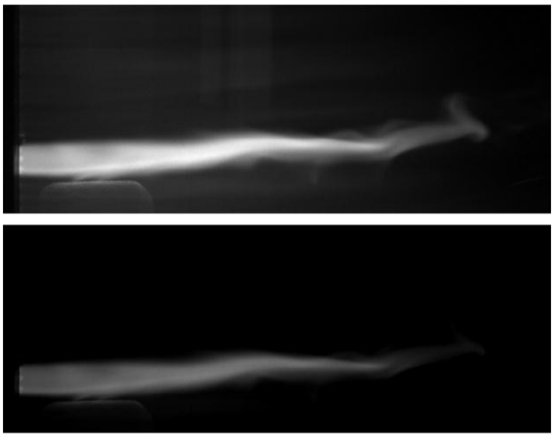

Figure 2. Views of the same plasma jet with different sensitivities of optical system (diameter at the nozzle exit is 6 mm).

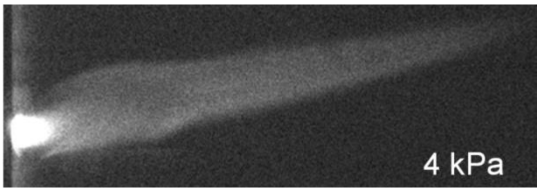

Figure 3. Plasma jet at reduced pressures conditions.

General principle of statistical processing of image sequences

Fig. 3. demonstrates basic principle of statistical processing of image sequence. Photographs 1-4 represents first 4 frames of image sequence. Processing of every point (pixel) is done independently. As example one point is marked by red star. Evolution of its brightness over the sequence of images is presented as green line on the following graph. It can be also represented by histogram of brightness values frequency. This distribution can be characterized by any statistical parameters as mean, median, standard deviation, skewness, kurtosis etc. In Fig. 3. an example of map of mean values and standard deviation values are shown. The mean image shows basic geometrical characteristics of the plasma jet while the standard deviation showing brightness deviation represents discharge fluctuations. Standard deviation based parameter was successfully used by authors in earlier paper [8]. However later analysis showed its inaccuracy in representation of fluctuations.

It is important that the statistical parameter that is in use has clear physical interpretation. Standard deviation can mean width of brightness values distribution and in such cases would be valid representation of fluctuations. However, direct correlation of standard deviation and distribution width is valid only for the Gauss distribution. Fig.4. demonstrates brightness values distributions in various regions of plasma jet. It can be seen that the Gauss distribution is not often the case. Asymmetrical shapes can be well fitted with gamma distribution while Gaussian shape became inapplicable. Other statistical parameters, skewness, kurtosis etc. were tested [9] but are less clear and disputable in meaning. That was the reason to search more general parameter.

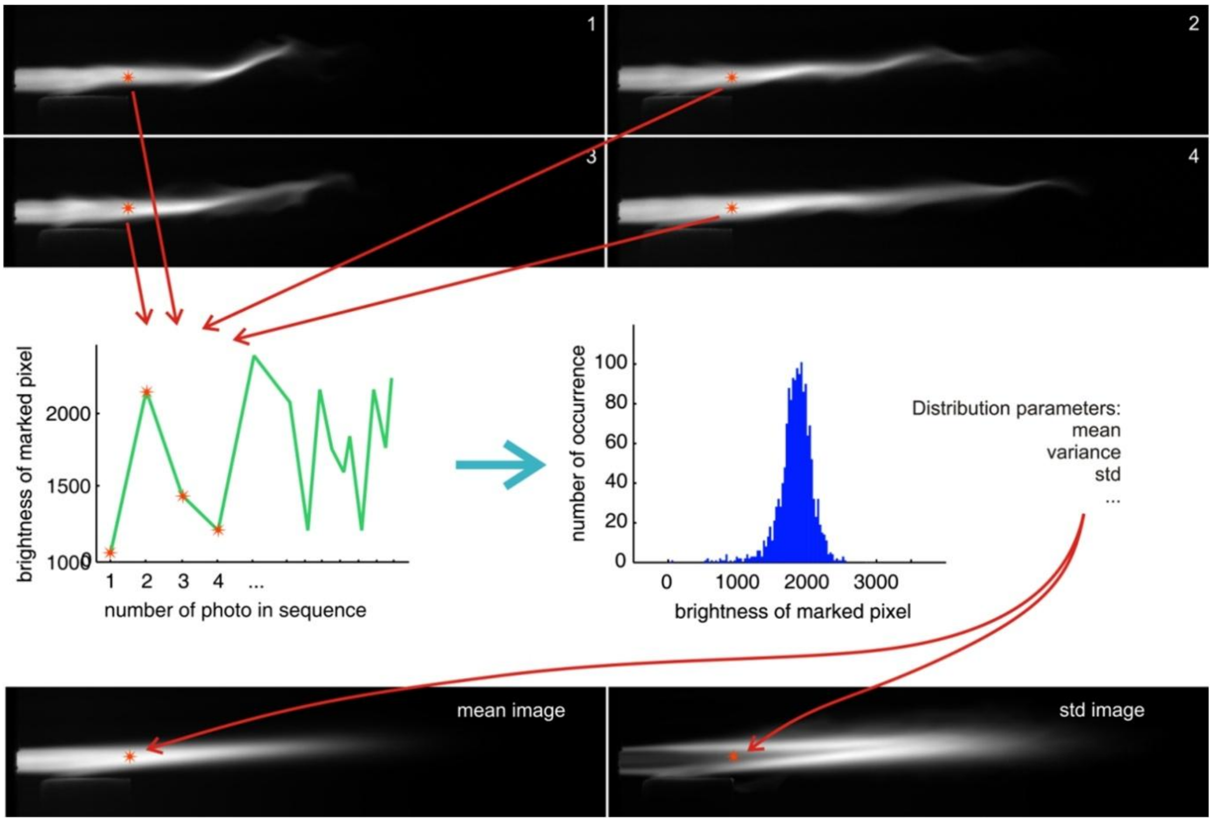

Figure 4. Presentation of principle of statistical processing.

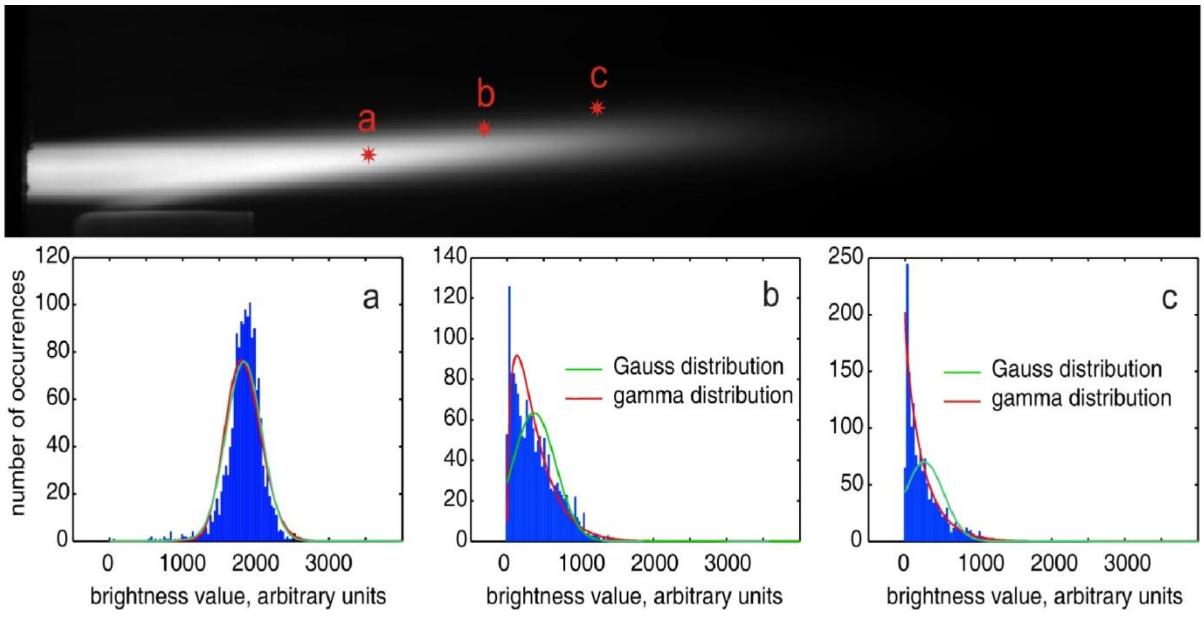

Figure 5. Brightness distribution shapes in different locations of plasma jet (a-centre of the jet, b-fringes, c-far fringes).

Using of Shannon entropy as general statistical parameter

In information theory, entropy is a measure of the uncertainty associated with a random variable [9, 10]. In this context, the term usually refers to the Shannon entropy, which quantifies the expected value of the information contained in a message. Entropy of brightness values for particular position of image can be calculated based on the histogram demonstrated in Fig.3 according to the following equation:

$$H(X) = -\sum_{i=1}^{n} p(x_i) \ln p(x_i), \tag{1}$$

where $H(X)$ is the entropy of a discrete random variable X with possible values $\{x_1,...,x_n\}$ and characterized by probabilities $p(x_i)$. The number received is value of information content in *nat* units. Higher number means higher information content and equal to higher degree of uncertainty. In order to transform the result back to measurement units of primary data exponent operation should be done: The result can be interpreted as efficient width of the brightness distribution:

$$W(X) = e^{-\sum_{i=1}^{n} p(x_i) \ln p(x_i)}. \tag{2}$$

The width of brightness distribution or amplitude of brightness fluctuation relates to total brightness and it would be beneficial to turn it into relative units. Comparison to reference distribution could be used. The maxim uncertainty theoretically has uniform distribution. Uniform distribution of the same brightness diapason as measured in current location can be used as the reference. Its entropy can be evaluated as follows:

$$H_u(X) = -\sum_{i=1}^{n} p_u(x_i) \ln p_u(x_i) = -np_u \ln p_u = -\ln\frac{1}{n} = \ln n, \tag{3}$$

where index u stands for uniform distribution and probability of all events is equal to p_u. Then calculation of effective width (2) will be changed to a ratio of widths of experimental distribution and uniform distribution. Result should be in relative unites between 0 and 1, lowest and highest uncertainty:

$$W(X) = \frac{e^{-\sum_{i=1}^{n} p(x_i) \ln p(x_i)}}{n} = e^{-\sum_{i=1}^{n} p(x_i) \ln p(x_i) - \ln n}. \tag{4}$$

This formula can be easily coded and used for digital processing. In Fig.6 example of histogram of brightness in the jet fringe is shown. Brightness lays in range of values from 88 to 1608. Whole range is divided on 10 regions and the bars have heights [176 70 29 13 7 3 1 0 0 1] and corresponds to values of relative frequency [0.5867 0.2333 0.0967 0.0433 0.0233 0.0100 0.0033 0 0 0.0033]. Entropy and effective width of this distribution are

$$H(X) = -(0.5867 \ln 0.5867 + 0.2333 \ln 0.2333 + \cdots + 0.0033 \ln 0.0033) = 1.1861,$$
$$W(X) = e^{1.1861 - \ln 10} = 0.327,$$

which is less than half of maximum fluctuation intensity of 1.

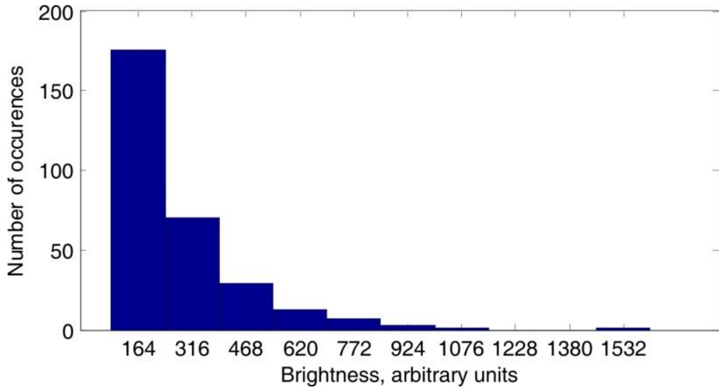

Figure 6. Histogram of brightness distribution in the fringe of plasma jet.

Example of plasma jet structure investigation.
Plasma jet generated with arc current of 400 A and total power of 120 kW was analyzed using the method. Effect of two parameters was observed. The fist was distance of anode from the plasma jet, which was changed from position visual contact 10 1 and 2.5 mm from the jet visual fringe. Second parameters was flow rate of argon, secondary plasma forming gas, which was increased in steps 12.5 slm, 17.5 slm, 22.5 slm. Sequence of 200 images with exposure time of 3 μs was taken for every condition. The brightness values diapason in every point was divided to 30 regions and described calculation were preformed. Fig.5 shows maps of relative entropy values. The relative entropy values are shown as color map pictures. Blue indicates the most stable regions and red the most uncertain.

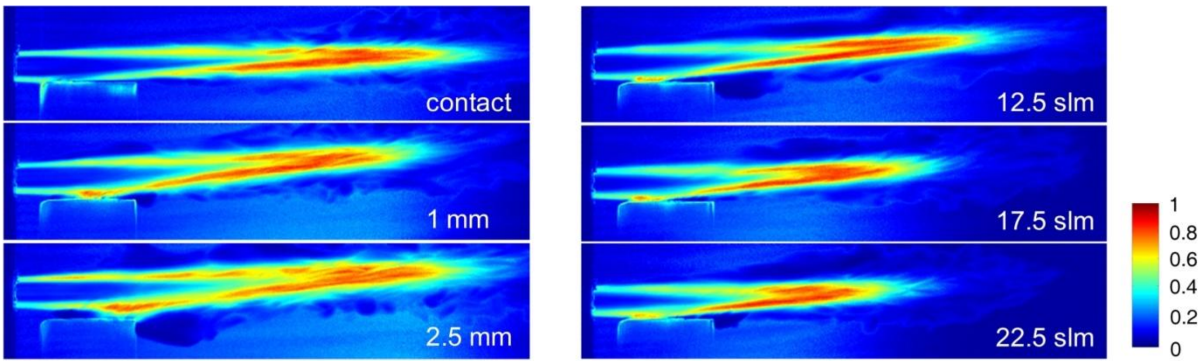

Figure 7. Maps of relative entropy of plasma jet in dependence on anode surface distance from the jet (left) and in dependence on argon flow rate (right).

Common structure of jet can be seen. Near the nozzle exit more intensive fluctuations occur in the jet boundaries and spreading downstream they finally join ending stable jet core. Distinguishable fluctuation region is an area where the arc attaches the anode surface. The jet slightly deflects at this point. Most intensive fluctuations are at the jet tip where deflection scale of plasma flow is probably comparable to the width of jet.

Anode position evidently influences the jet structure. Most stable jet was generated at the situation when anode toughs jet fringe. Current way was simplified and arc-anode connection did not caused disturbances. For other cases longer current path meant appearance of jet fluctuations in the anode region its development along the jet and shortening of stable jet core. Plasma jet became shorter for the case of 1 mm gap between the jet and anode. However distance of 2.5 mm in spite of similar development of fluctuations led to longer jet. It could be caused by increase of plasma power due to longer arc and due to movement of arc-anode attachment in direction perpendicular to the picture orientation. This movement led to spreading of disturbances and lower effect on jet stability.

Increase of argon flow rate leads to shortening of the plasma jet. It causes more intensive boundary fluctuations in the jet beginning. Boundary fluctuation regions also join more rapidly for higher argon flow rate. The pattern of jet tip fluctuation changes significantly as well. The pictures demonstrate that argon flow rate significantly changes plasma jet structure and stability, which in this case can be motivation for further research.

Conclusion

The method of fluctuation intensity visualization is presented as powerful tool in stability analysis. The map of a statistical parameter of local brightness variation is suggested to be used for visualization of flame and discharge structure. Information entropy concept as brightness distribution characterization brings to the method strong mathematical background and clear result interpretation. It is possible to generate relative values, which are free from absolute brightness influence. It makes the method less dependent on experimental setup parameters and simplifies its interpretation. The maps of relative brightness fluctuation intensity based on entropy concept are demonstrated to be good visual representation of plasma flow structure.

Acknowledgements

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