

SUSPENSION PHASED-INJECTION IN SELF-SUSTAINED PULSED ARC JET

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ABSTRACT

The arc instabilities in dc plasma torch result in non-homogenous treatment of material injected into the plasma jet. The improvement of this process is usually attempted by means of the reduction of arc fluctuations. This paper presents a new approach to overcome the plasma instabilities. The emphasis is to produce a pulsed laminar plasma jet combined with phased injection of liquid droplets. This is achieved by the particular design of the plasma torch which allows coupling two modes of the plasma oscillations, restrike and Helmholtz. It results in the pulsed arc jet which permits to synchronize the plasma with the suspension injection. This synchronization is obtained by a piezoelectric injector triggered by the voltage signal. The results are evaluated by time-resolved imaging technique and Time-Resolved Optical Emission Spectroscopy.

1. INTRODUCTION

Direct current plasma torches are widely used in thermal spraying techniques, particularly in the latest researches for forming nanostructured coatings by the suspension plasma spraying process. However, in more complex applications, the researches face many problems due to, among other things, high fluctuations of the plasma jet. One of the sources of these instabilities is the 'stick and slip' motion of the arc inside the nozzle [1-2]. This kind of oscillations, known as 'restrike' mode, gives an irregular voltage signal approximately saw-tooth in shape. The other major source of the plasma fluctuations has been more recently identified in conventional plasma torches [3-4] and related to compressibility effects of plasma forming gas in

the cathode cavity. These instabilities appear in power spectrum of the arc voltage as a strong, sharp peak (2–5 kHz), and have been referred to Helmholtz mode. The objective of this paper is twofold. First, it is proposed to show the possibility of coupling Helmholtz and restrike modes in a mechanism of phase-locked loop to obtain pulsed arc jet. This type of periodic pulsed plasma, provided the use of synchronous injection, is expected to improve the control of dynamic and thermal interaction between the plasma and injected material. Second, the diagnostics of plasma by Time-Resolved Optical Emission Spectroscopy is presented. In the future this kind of measurement is expected to give a better understanding of phenomena implied in chemical kinetics of heat transfer between the plasma and the imbedded materials.

2. MOSQUITORCH

As has been highlighted above, in the plasma jet generated by dc torch the oscillations modes, restrike and Helmholtz, have been identified. The following paper shows the possibility of coupling these two modes to obtain pulsed laminar arc plasma jet [5-6]. This process is able to obtain by a special torch characterized by a larger cathode cavity ($V_g=17.8 \text{ cm}^3$). The study of Helmholtz mode shows that the resonance frequency, f_H , linked to this oscillation, depends on: $f_H=1/2\pi(\gamma_g \cdot p_g / \rho_p) \cdot (S/L_p \cdot V_g)$ where γ_g , p_g are, respectively, the isentropic coefficient of the cold gas, the mean pressure in cathode cavity, ρ_p is the plasma density, S , L_p and V_g are, successively, the cross section area, the length of the nozzle channel and the volume of the cathode cavity. The design of a larger cathode cavity in the torch, following the equation above, allows decreasing the Helmholtz mode frequency and reinforcing the Q factor. Nitrogen is used as

plasma gas with mean mass flow rates, \bar{m} , between 0.042 and 0.104 g.s⁻¹ and different nozzles are tested with channel diameters, d , of 2.5, 3, 3.5 and 4 mm.

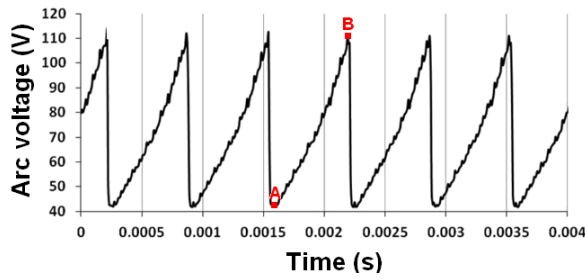


Fig.1 Arc voltage signal for: $d = 4$ mm, $I = 14.9$ A, $N_2: 0.042$ g.s⁻¹, $\bar{V} = 74$ V.

By adjusting these operating parameters and the arc current, a very regular voltage signal, presented in Fig. 1, has been obtained. This new resonant mode of the torch has been called mosquito mode because the sound produced by that torch recalls the flight of a mosquito. For each experiment the heat losses, Q_{loss} , to the electrodes are measured together with the electric power supplied to the torch, P_{elec} . The mean specific enthalpy of the plasma is calculated by the equation: $h = (P_{elec} - Q_{loss}) / \bar{m}$. The energy balance measurements and the calculations [5-6] have highlighted that specific enthalpy in the mosquito mode is modulated in the proportion, $h_{max}/h_{min} = 13$, with a mean value of 13.3 MJ.kg⁻¹.

3. EXPERIMENTAL

The suspension spraying system, used in the experiment, consists of a new home-made torch described above, equipped with an external injector based on the drop-on-demand (DOD) method, presented in Fig. 2.

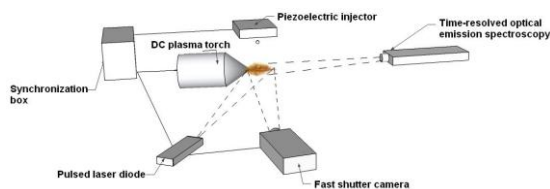


Fig. 2 Experimental setup.

The principle of this method, commonly used in the inkjet printing, is the injection of a material due to the pressure generated by a voltage pulse driven piezoelectric actuator. The piezoelectric injector, used in the experiment, allows obtaining

a single calibrated droplet of TiO₂ suspension (42 wt% of powder and 58 wt% of water) per trigger with a diameter of 50 μm and a velocity adjustable between 2 and 10 m.s⁻¹. The emission of each droplet is synchronized with the pulsed plasma jet by trigger signal obtained from sampling of the torch voltage after an adjustable delay, τ . In the experiment, the injection time delay varies from 0 to 620 μs, where 0 μs corresponds to the lowest level voltage (~ 40 V). The plasma-suspension interaction is observed by time-resolved imaging system composed of a fast shutter camera (PCO, Kelheim, Germany) coupled with a laser (HiWatch, Oseir, Tampere, Finland). Both the camera and the laser are synchronized with the injection by the synchronization box. The pulsed laminar arc jet is diagnosed by the Time-Resolved Optical Emission Spectroscopy (TROES) which consists of an IsoPlane spectrograph (Princeton Instruments, Trenton, New Jersey) equipped with 1200 g/mm gratings. The spectra acquisition is realized by using a PI-MAX4 ICCD camera (Princeton Instruments) connected to the PC and controlled by LigthField software. All measurements are performed with a spectral slit width of 300 μm, On-CCD accumulations number equals to 100 and the gate width of 60 μs.

4. RESULTS

Fig. 3 presents the pulsed plasma jet with: A) low level of local specific enthalpy which corresponds to the lowest voltage level, A, in Fig. 1. Fig. 3 B) shows the plasma with high level of local specific enthalpy, B in Fig. 1. The spectroscopic measurements of the nitrogen pulsed plasma have been carried out for the jet presented in Fig. 3 B). The two distances of 1 mm and 5 mm from the nozzle exit have been tested, what is shown in Fig. 3 B).

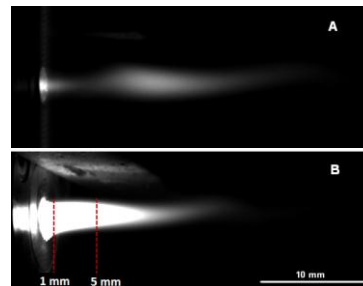


Fig.3 Pulsed arc jet with: A) low level of local specific enthalpy, B) high level.

Fig. 4 presents the emission spectrum of the first negative system of the N_2^+ molecule ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$) obtained at a distance of 1 mm from the nozzle. The rotational temperature, T_{rot} , has been calculated by using Specair software, which allows comparing the experimental and simulated spectra. The measured spectrum has been fitted to the theoretical one, what is presented in Fig. 4. Well-fitted rotational structures permit to determine the rotational temperature with good accuracy.

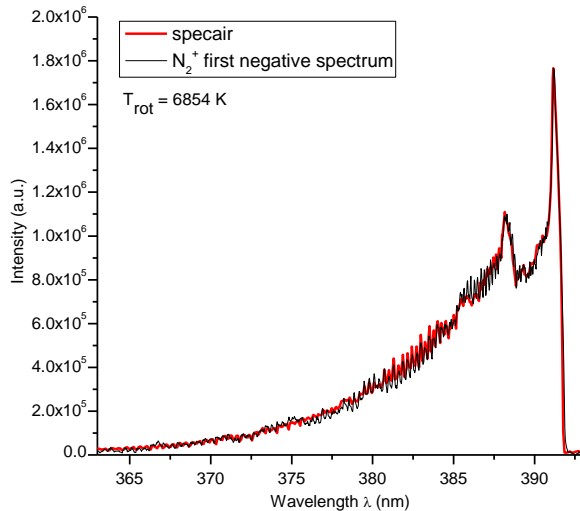


Fig.4 Comparison of the measured and simulated by Specair software (N_2^+) first negative spectra.

Fig. 5 highlights the spectroscopic measurements obtained for the distance of 1 mm and 5 mm.

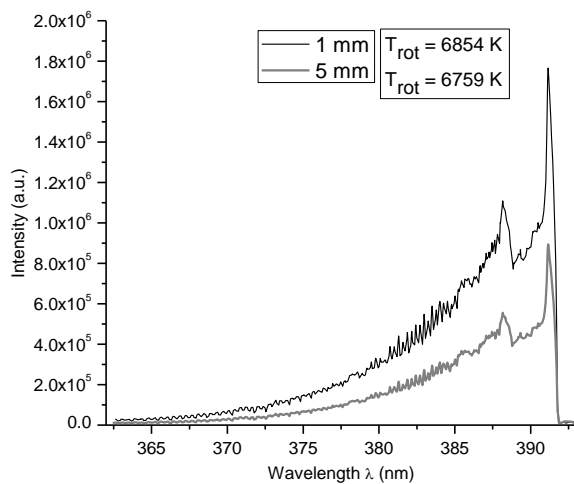


Fig.5 (N_2^+) first negative spectra for the distance of 1 mm and 5 mm from the nozzle exit.

Analyzing the N_2^+ molecule emission at 391 nm, it can be observed that the spectrum measured in 1 mm is characterized by the higher value of the intensity than the spectrum detected in 5 mm with T_{rot} relatively similar within the data

processing error. The observed differences in the values of the intensity can be explained by analyzing the cross-section of the plasma jet in Fig. 3 B). In the distance of 1 mm from the nozzle exit the plasma jet is wider than in 5 mm, what corresponds to a higher intensity level in spectral measurements. Moreover, in the spectrum obtained in the distance of 5 mm CN violet system ($B^2\Sigma^+ - X^2\Sigma^+$) at 388 nm has been observed, what demonstrates the mixing of the plasma jet with the surrounding air that contains the trace of CO_2 .

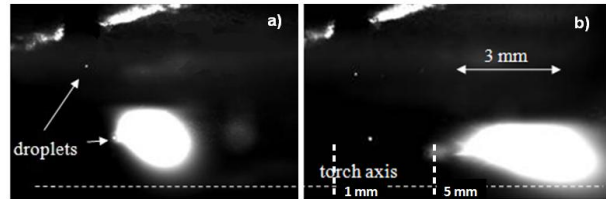


Fig.6 Synchronized material injection to plasma jet with: a) high level of local specific enthalpy, b) low level.

Fig. 6 presents the main objective of this paper, the synchronized material injection to the pulsed plasma jet. On these pictures the suspension droplets appear as tiny white dots and are visible thanks to the laser illumination. The plasma itself, which flows from the left corner of the picture, cannot be seen because it is not sufficiently luminous to be captured by the camera. Instead of that, the cloud resulting from the plasma-droplet interaction appears clearly as a “plasma ball”, testifying of a strong increase of the brightness of the seeded flow, what is visible with naked eye. Fig. 6 a) shows the case where the plasma is characterized by high level of local specific enthalpy. When the droplet enters the jet the vaporization-seeding process is observed almost immediately. The reverse situation is shown in Fig. 6 b). The droplet is injected to the plasma with a low level of specific enthalpy. At that time the vaporization-seeding process does not concern this droplet but the injected one period earlier and it gives the plasma ball at the right of the Fig. 6 b). The spectroscopic measurements obtained for the different distances from the nozzle exit show the possibility of analyzing the phenomena occurred in the vaporization-seeding process, what will be investigating in a future work.

5. CONCLUSIONS

The possibility of phase locking Helmholtz oscillation and rearing events in the nozzle has been presented. It results in a new resonant mode, called “mosquito” mode, which shows a very regular saw-tooth shaped arc voltage. The local specific enthalpy of the pulsed plasma jet, obtained in this mode, is modulated with a ratio $h_{\max}/h_{\min}=13$, with a mean value of 13.3 MJ/kg. This modulation can be used to synchronize the plasma with the material injection. The system based on drop-on-demand method has been selected to inject the suspension in a chosen moment. The interaction between the plasma and the droplets has been examined by time resolved imaging techniques triggered by arc voltage signal and synchronized with suspension injection. The presented method is expected to control the dynamic and thermal interactions between plasma and injected material, what will be investigating in a future study. The plasma jet has been diagnosed by using Time-Resolved Optical Emission Spectroscopy which has allowed performing the spectroscopic measurements in different distances from the nozzle exit. The spectroscopic diagnostics show that the rotational temperature of N_2^+ decreases along the plasma jet and the surrounding air has the higher influence on the plasma while increasing the distance from the nozzle exit. TROES analysis of these phenomena will be continued in a future work.

6. ACKNOWLEDGMENTS

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