TIME RESOLVED MEASUREMENTS OF ARC VOLTAGE, TEMPERATURE AND VELOCITY IN A D.C. PLASMA TORCH

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Abstract

The dynamic behavior of the plasma flow produced by d.c. spray plasma torches has been studied by measuring arc voltage fluctuations, velocity and temperature distributions and fluctuations. The plasma velocity was determined by an optical method based on the natural fluctuations of the jet and the temperature was obtained from emission spectroscopy with a special data processing taking into account the temperature fluctuations. The experiments were realized in a chamber which could moved vertically and horizontally permitting to characterize all over the jet. Moreover, the collected data used for both velocity and/or temperature determination were simultaneously sampled with the arc voltage recording. So, the fluctuating components of both velocity and temperature could be correlated to the arc voltage fluctuations.

INTRODUCTION

There is an increasing amount of work which is nowadays devoted to the instabilities occuring in the plasma jets generated by commercial plasma torches /1-7/. It is now clearly believed that the instabilities, despite their real sources or origin, are implicated in the overall flow structure, namely via the air entrainment mechanism which controls the plasma jet dilution. In the same time the resulting flow pattern is characterized by strongly fluctuating velocity and temperature fields, for which no time resolved measurement was carried out, as far as arc jets were concerned.

However, numerous experimental studies were performed in the past to investigate plasma spray jets. Most of them were devoted to "time averaged" temperature measurement by applying either spectroscopic techniques or probe techniques /8/. To a lesser extend, the velocities were measured by various techniques, one of the most commonly encountered being Laser Doppler Anemometry /9/. In addition, a very few works /1,10/ in the litterature mentioned experimental data for the velocity fluctuating component or turbulence intensity in d.c. plasma jets.

The aim of this paper is to present the first results of a recent study concerning the instabilities of the electric arc, thermally constricted by the nozzle of a d.c. plasma torch, in connexion with the fluctuations of the temperature and the velocity measured in the plasma flow at the nozzle exit.

THE ARC VOLTAGE

In a classically configurated plasma spray torch, if the arc geometry is rather simple in the vicinity of the cathode tip, where the arc column shows a cylindrical symmetry, the arc exhibits a complex and changing shape in the arc-anode attachment region, under the influence of gas dynamic and magnetic body forces.

The modifications of the morphology of the arc are associated with typical features of the recorded voltage which gives a sawtooth shaped waveform with linear increasing ramps followed by negative voltage jumps (fig.1). The slope of the ramps indicates the rate at which the arc and the imbeded current lines are stretched and lengthened by the flow. Each of the lengthening phase is limited by an electrical breakdown through the cold and electrically insulating gas layer surrounding the arc. Each breakdown initiates a short circuit, together with a new arc attachment at the nozzle wall, and is associated with a negative jump of the voltage. This situation is corresponding to the so called "restrike mode" /11/ and has been reported in the past by different experimental investigators /11-13/. More recently a statistical study was conducted for the determination of the tendencies shown by the characteristics of the arc voltage fluctuating components /7/.

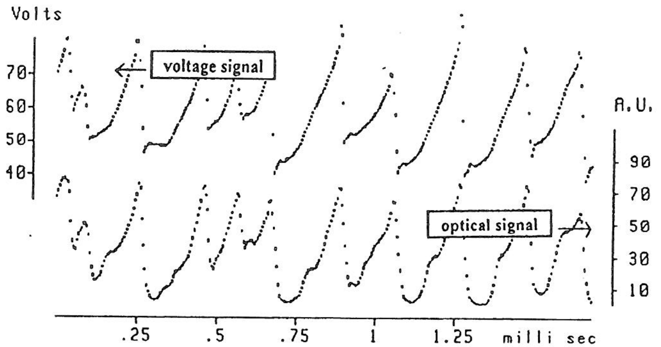

fig.1 : Comparison between the arc voltage (top) and the optical signal (bottom)

It was found that the mean jump amplitude, together with the stagnation time of the arc attachment, depend on the torch operating parameters in a way which can be described by semi-empirical relationships. Rather good correlations were obtained testifying of a better insight of the underlaying arc dynamic.

The result of such arc instabilities is to induce strong fluctuations of the instantaneous electrical power supplied to the gas and, as a consequence of the energy balance, of both the local temperature and velocity of the flow. Fig.1 shows the correspondence between the arc voltage and the wavelength integrated light emitted by the plasma core and sampled 2 mm downstream of the nozzle exit (see fig.2). The similarity between these two signals suggested that a strong coupling exists between the arc voltage variations and those of the parameters required for the plasma flow characterization.

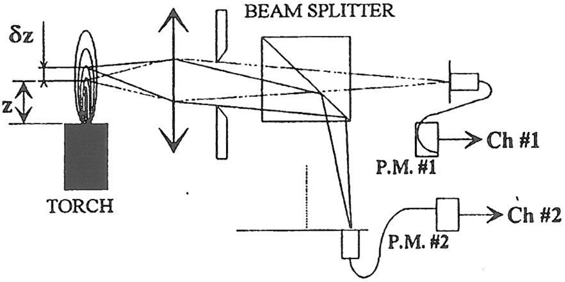

fig.2 : Experimental set up for velocity measurement

VELOCITY

The axial velocity of the plasma flow was measured thanks to the experimental arrangement presented in fig.2. The principle of the method /14/ is to determine the time of flight of the luminous fluctuations sampled in two different points of the flow. The delay is obtained from the shifted maximum of the cross-correlation function of the two "optical" signals. Taking into account the specificities of the method (number of data points for the digitized signals, sampling rate), each single velocity obtained corresponded to a value which was time averaged over a 2 millisecond period. In other words, that means that the method shows a low frequency band pass limited to approximately 500 Hz.

In order to compare the time variations of the measured velocity (in a given point of the plasma jet) with those of the synchronously recorded arc voltage, this last one, which spectrum is spread over a wide frequency range (up to 50 kHz), was numerically convoluted by a smooth-edge temporal window, 2 millisecond in width. A typical result is presented in fig.3, obtained for the following working parameters : nozzle diameter : 7 mm; Arc current : 300 Amp; Gas flowrate : 60 slm Ar-H2 mixture (75%/25% vol).

The similarity between the two waveforms testifies of a rather strong coupling between the voltage and the velocity. In such circumstances, the plasma flow appeared to be pulsed at the same rate than the electrical energy supplied to the gas, at least for the low frequency components which were lying in the measurement band pass. The velocities in fig.3 were measured on the jet center line, 2 mm downstream of the nozzle exit. the same kind of similarities was observed at different locations in the jet provided the velocity was measured in the potential core, outside of which the correlation could not be brought out. In such a situation, the low frequency fluctuations of the velocity in the vicinity of the nozzle exit could be seen as the reflect of the arc instabilities taking place in the upstream direction.

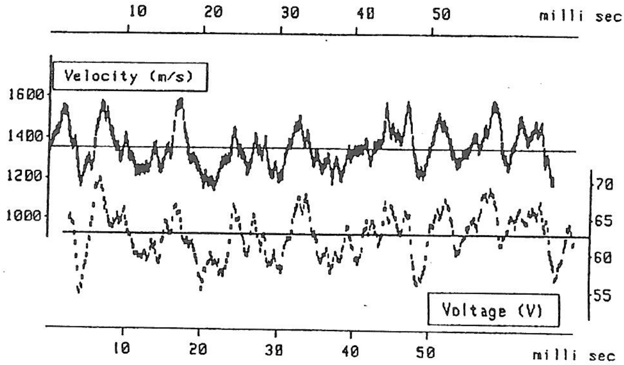

fig.3 : Comparison between the arc voltage (bottom) and the flow velocity (top).

TEMPERATURE

Assuming the plasma to be in local thermodynamic equilibrium (L.T.E.), the temperature was measured by optical emission spectroscopy, applied to the absolute intensity of an ArI line. The line intensity was recorded accross the width of the jet by side on measurements, thanks to an optical system equipped with a rotating mirror. The light incomming the exit plane of the scanning system was sampled by an optical fiber and driven to a Jobin-Yvon monochromator (H.R.S model). The detection was ensured by a photomultiplier which output was connected to a digital oscilloscope operated at a 10 µs/point sampling rate and triggered by the rotating mirror.

Taking into account the angular velocity of the mirror together with the focal length of the optical system, a single line intensity profile was recorded within 20 millisecond approximately. The recorded profile showed a fair amount of noise which was due to the instabilities of the flow, rather than an extra perturbating phenomenon.

More precisely, it was believed that the fluctuations of the local temperature were responsible of the strong variations observed for the line intensity, in the same way than for the wavelength integrated light intensity (see fig.1).

The link between the temperature and the recorded fluctuating intensity is schematically represented on follows :

L.T.E — optically thin plasma

$$T(\vec{r},t) \rightarrow \varepsilon(\vec{r},t) = K(T).e^{-\frac{E_j}{kT}} \rightarrow I(y,t)$$

where I(y,t) is the atomic line intensity sampled at the time t, y being the distance between the line of sight and the jet axis.

ε is the volumic emission coefficient, K(T) involves, among other things, the number density and partition function of the atoms /15/, E_j is the energy of the upper level of the atomic transition.

As it is suggested above, it is not straightforward to get the local and fluctuating temperature provided the unique knowledge of the recorded profile I(y,t). Nevertheless, a very few work, devoted to specific situations, have been conducted in the past to take into account the effects of instabilities /16-17/.

Concerning the work presented here, a model for the data treatment based on the signal theory, similar to the one described in /3/, was set up to take into account both the instabilities, despite their origin, and the non linearity occuring in the emission coefficient formulae. This model required several assumptions, among which it was believed that :

-The cylindrical symmetry is preserved despite the fluctuations.

- The temperature fluctuations are described by a dimensionless function $n_T(t)$, so that :

$$T(r,t) = T_s(r).(1+n_T(t))$$

where $T_s(r)$ is the stationnary temperature profiles for a given cross-section of the plasma jet.

The model allowed to obtained $T_s(r)$ together with $n_T(t)$ from a single record of I(y,t). In addition, $n_T(t)$ was compared with an analogous function, $n_V(t)$, deduced from the synchronously recorded voltage V(t), with :

$$n_V(t) = \frac{V(t) - \overline{V}}{\overline{V}}$$

where $\overline{V}$ is the time averaged arc voltage.

A comparison was made between the temperature profile obtained from the noise eliminated intensity profile, using a classical data smoothing technique, and $T_s(r)$. It was found that, because of the non-linearity together with the fluctuations, the classical data processing technique gave a maximum temperature overestimated by 500 K approximately, when $T_s(0)$=12000K.

The reconstructed T(r,t) profile is presented in fig.4 for the following operating condition : nozzle diameter : 7 mm; current intensity : 600 Amp; Ar-H2 (75/25 % vol) : 60slm.

The data were collected 2 mm downstream of the nozzle exit. The stationnary profile (black curve) shows a maximum temperature about 12000 K and a standard deviation about 970 K (which corresponded to $\sqrt{\overline{n_T^2}} = 0.08$). The dimensionless fluctuating components of the temperature , $n_T(t)$, and of the voltage , $n_V(t)$, are plotted together in fig.5. Eventhough the corresponding details don't wear the same shape, a qualitative correspondence can be noted between the two waveforms. The statistical distributions of the amplitudes as well as the respective standard deviations, indicate that the fluctuations of the temperature are approximately two times lower than the voltage fluctuations, this fact being attributed to the damping due to the thermal inertia and to the thermal diffusion.

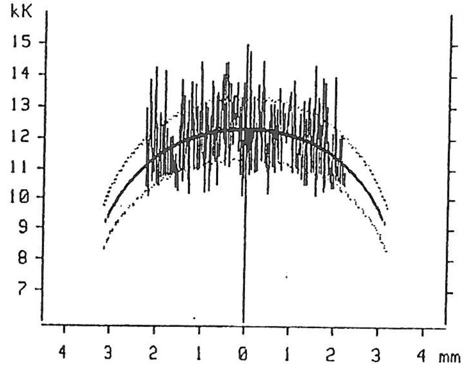

fig.4 : Temperature measured 2 mm downstream of the nozzle exit.

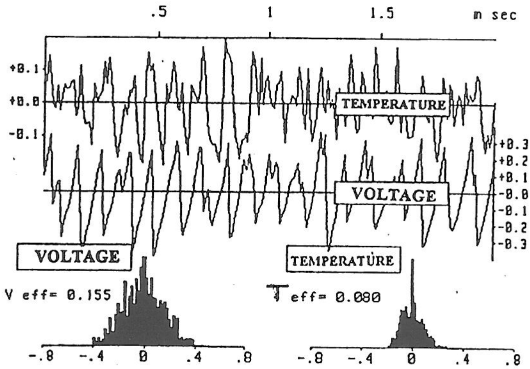

fig.5 : Comparison between the reduced arc voltage, $n_V(t)$, and the reduced fluctuating temperature, $n_T(t)$.

The 10 μs/point sampling rate used for the dizitizing process allowed to compute the power spectrum of $n_T(t)$ and $n_V(t)$ up to 50 kHz. The results are presented in fig.6 where a sharp isolated pic can be noted for the voltage, approximately at 9 kHz.

This particular frequency was due to the operating conditions used here, and may change significantly with other working parameters /5/. In the case of the fig.6, the same frequency peak appeared in the temperature spectrum, testifying together with fig.5 of an efficient coupling between the temperature and the voltage fluctuating components.

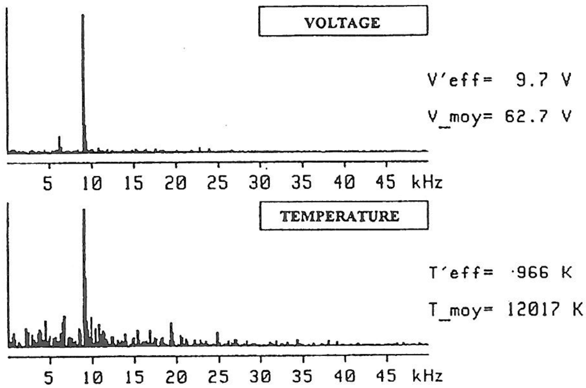

fig.6 : Power spectra of the reduced voltage (top) and temperature (bottom)

CONCLUSION

Different experiments were conducted to investigate the influence of the arc instabilities on the parameters which described the plasma flow produced by a d.c. plasma spray torch. The electric arc is thermally constricted by the anode-nozzle and is submitted, on the one hand, to the gas dynamic force which is responsible of the current lines lengthening, and on the other hand, to the breakdowns through the cold gas layer which are shortening the arc column by initiating new anode-arc attachments. The balance between these two effects led to a dynamic equilibrium, characterized by strong fluctuations in the arc voltage. As a consequence, the induced plasma flow exhibited a fluctuating structure and rather well defined correspondences were brought out showing the coupling between the voltage instabilities and the fluctuations of the velocity and of the temperature.

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