DYNAMIC AND STATIC BEHAVIOURS OF DC VORTEX TORCH WORKING WITH H_2 AND Ar-H_2

ERIN J., PATEYRON B., DELLUC G., FAUCHAIS P., LABROUSSE M.*, BOUVIER A.**

Equipe P.L.M,Lab. "Matériaux Céramiques et Traitements de Surfaces"
123, Av. A. Thomas, 87060 LIMOGES, France
EDF, D.E.R., Applications de l'Electricité et Environnement*,
Applications de l'Electricité dans l'Industrie**,
Les Renardières B.P 1, 77 250 MORET-SUR-LOING, France

Abstract:

It has been shown recently that hydrogen or argon-hydrogen plasma jets are efficient means for the pyrolysis destruction of carbofluorine wastes, because they avoid the production of very toxic species such as phosgens or cyanides. This work is devoted to the study of the production of argon-hydrogen or pure hydrogen plasmas. The dynamic and static behaviours of a D.C vortex plasma torch with a button type thoriated tungsten cathode and a tubular anode (d= 8mm) were studied. The influence of arc current (I), gas flowrate (G) and composition on the static and dynamic torch characteristics was investigated. To characterize the static behaviour of the torch, the variations of the arc voltage (U) and thermal efficiency (η) with I, G, gas composition were represented by semi empirical relationships. The dynamic behaviour study, in progress, was founded on the analysis of the voltage fluctuations and measurement of characteristic frequency peaks of the arc column-anode wall disruptions.

I. Introduction.

The aim of this work was the investigation of the behaviour of a D.C vortex plasma torch working with argon-hydrogen or pure hydrogen plasma forming gases. The optimum working conditions were searched, i.e those corresponding to a good thermal efficiency and a low electrode erosion.

The techniques of investigation were developed on the basis of dimensionnal analysis for the static [1-6] and dynamic behaviours [7,8].

II. Design of the torch and experimental set up.

The torch used has been designed and developed in the laboratory. It is a modular tool composed of a button type cathode, a gas chamber adapted for vortex injection, and an anode (with constant internal diameter (i.d.) or with a step diameter change) (figure 1). The button type cathode was made of thoriated tungsten (W+2wt%ThO_2, Ø = 10 mm) brazed in a copper water cooled holder. The anodes were made of OFHC copper, 110 mm in length and 8 mm in i.d, also water cooled under a pressure of 1.4 MPa.

The torch power supply was a DC source (diode rectifier with an hexaphasis Graetz bridge). The studied working parameters were total gas flowrate G(slm), hydrogen percentage x(%) and current intensity I. The voltage fluctuations were studied by using a 4 tracks digitizing oscilloscope (LeCroy 9314 M) and a Fourier Analyser (Tektronix 2622) connected to a micro-computer for signal analysis and storage.

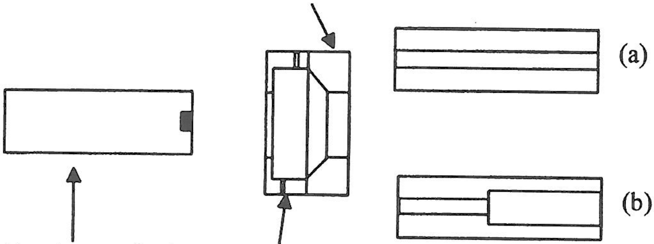


Figure 1: Scheme of the D.C vortex torch

III. Characteristics of plasmas containing hydrogen.

When considering Ar-H_2(x vol%) mixtures with x varying from 0 to 100% the electrical conductivity does not depend very much on x and the plasma is electrically conductive for T≥ 8000 K[9], temperature T_e which defines the arc column electrical radius r_e (mm). r_e depends strongly on the mixture mean integrated thermal conductivity $\bar{\kappa}(\bar{\kappa} = \int_{Tw}^{Te} \kappa(s)ds/(Te - Tw))$[9]. The calculation of r_e developed by J.F Coudert at the laboratory with a simple model derived from that of Stine and Watson[10] shows that, for a hydrogen plasma, r_e is rather small compared to the anode radius(table 1) while with Ar-H_2 plasma, and almost independently of the gas flowrate, r_e is close to the anode radius as soon as I=400 A.

Beside the lowest molecular viscosity of H_2 compared to that of Ar or any Ar-H_2 mixture (see table 2), the main problem with H_2 is its very low mass compared to that pure Ar or Ar-H_2 mixtures. Thus the efficiency of the vortex drops drastically when the plasma forming gas is pure hydrogen and the drag force exerted on the tiny plasma column joining the anode and the arc column is also reduced due to the low dynamic viscosity of pure H_2 plasmas.

I (A)	Ar-H_2(25%) G=60 slm	Ar-H_2(25%) G=90 slm	H_2 G=180 slm
200	2.9 mm	2.82 mm	2.1 mm
400	3.4 mm	3.38 mm	2.54 mm
600	3.5 mm	3.45 mm	2.81 mm

Table 1. Calculated values of r_e for three current intensity values for a hydrogen and Ar-H_2 plasmas (*8 mm anode i.d.*).

Gas	Ar(60 slm)	Ar(60 slm) H_2 (30 slm)	Ar(60 slm) H_2 (90 slm)	H_2 (180 slm)
G_{mass} $(kg.s^{-1}).\ 10^{-3}$	1.78	1.83	1.92	0.27
μ $(kg.m^{-1}.s^{-1})$	1.198 10^{-4}	1.145 10^{-4}	1.039 10^{-4}	4.724 10^{-5}

Table 2. Differences between the mass flowrates and dynamic viscosities for pure Ar, H_2 and Ar-H_2 mixtures. (ν *was calculated at 3000 K mean temperature of the cold boundary layer surrounding the plasma column)*

IV. Study of the static behaviour

IV.1 Dimensionless relationships

The semi empirical relationships were calculated between dimensionless numbers [2], depending on working parameters. In case of static evolution, the numbers used were the following :

$$Su = \frac{Ud\sigma_0}{I}, Si = \frac{I^2}{Gd\sigma_0 h_0}, Re = \frac{G}{\mu_0 d}, \mathrm{Pr} = \frac{\mu_0 h_0}{\kappa_0 T_0}$$

where U, d, I, G, σ_0, h_0, μ_0, κ_0 were respectively voltage, anode i.d, current intensity, gas flowrate, electrical conductivity, enthalpy, dynamic viscosity and thermal conductivity calculated at a mean temperature T_0 (reference temperature corresponding to an electron density of about 1% and close to that defining r_e [2]).Such numbers allowed to determine empirical relationships U and thermal efficiency η evolution with I and G.

IV.2 Evolution of arc voltage with experimental parameters

The following equation(1) allowed to built arc characteristics U-I in different working configurations with pure Ar and pure H_2 :

$$Su = 2.22Si^{-0.670}.Re^{-0.123}.\mathrm{Pr}^{-0.524} \quad (1)$$

The investigated parameters range was 100 to 600 A for I and 60 slm to 440 slm for G. The arc characteristics were always decreasing but as it could be expected this effect is more noticable for low currents and for hydrogen plasmas. In fig. 2, this phenomenon is clearly represented for argon and hydrogen plasmas. A good agreement can be observed between computed and experimental data. For a constant I, U increases with a rise of G.

In case of argon-hydrogen plasmas, for a constant I, U increases with arise of hydrogen content mainly because of the increase of integrated κ of the mixture, σ and μ being almost insensitive to x for x>90. However this increase is less than that expected from the Su values when shifting from an Ar-H_2 mixture to a pure H_2 plasma. This due to the lower values of the viscosity and the mass flow rate of the gas resulting in an arc striking closer to the anode nozzle entrance with pure H_2 than with Ar-H_2 . Nevertheless, we could not find a good agreement between the experimental data and the calculated ones for the argon-hydrogen mixtures. This is probably due to the non linear effect of the mass of the mixture wich is not accounted for by eq. 1.

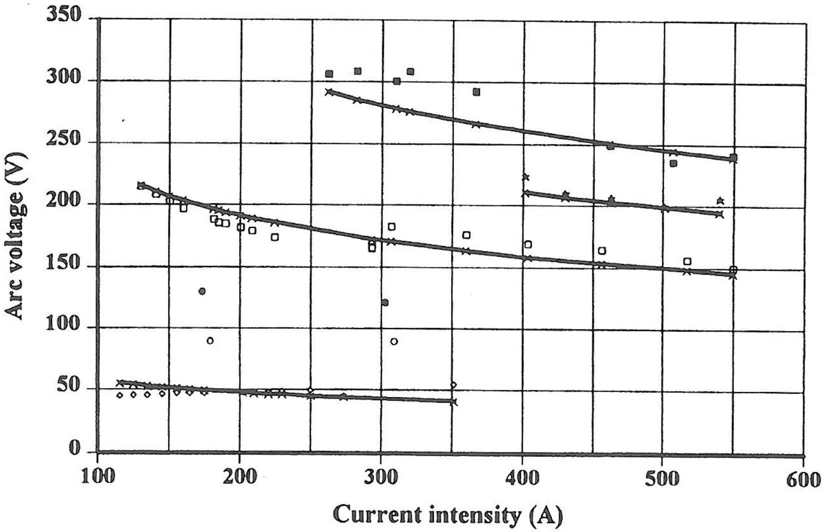


Figure 2: Experimental and calculated arc characteristics U-I for argon ✧ (G=60 slm) and hydrogen □(G=180 slm), ★(G=300 slm), ■ (G=440 slm) plasmas and experimental datas for two Ar-H_2 mixtures (O: 60 slm Ar, 30 slm H_2, ●: 60 slm Ar, 90 slm H_2 *(anode with a 8 mm i.d.)*.

III.2 Evolution of the thermal efficiency

The plasma torch can be considerated as a closed system and so the supplied electrical power is dissipated in the plasma and in the electrodes walls. Then equation (2) gives the expression of the thermal efficiency η :

$$\eta = 1 - \frac{P_e}{U.I} \quad (2)$$

where : P_e (W) : are the thermal losses at the electrodes calculated from calorimetric measurements on cooling water.

Generally, η decreases with the rise of I mainly because of the increase of the losses at the anode with I. An increase of G reduces convection heat losses at the anode walls leading to an improvement of the thermal efficiency (see fig. 3). For hydrogen plasmas, we found the relationship (3) linking η to I and hydrogen flow rate (for a 8 mm i.d. anode):

$$\eta = 35.58.I^{-0.246}.G^{0.337} \quad (3)$$

According to the coefficient signs attributed to I and G, the related behaviour of η is pointed out. Figure 3 shows too that to keep η between 0.6 and 0.7 G has to be only of 180 slm for I<250A while G has to be increased up to 420 slm for 400<I<550A. A quite good agreement can be observed between experimental and calculated data.

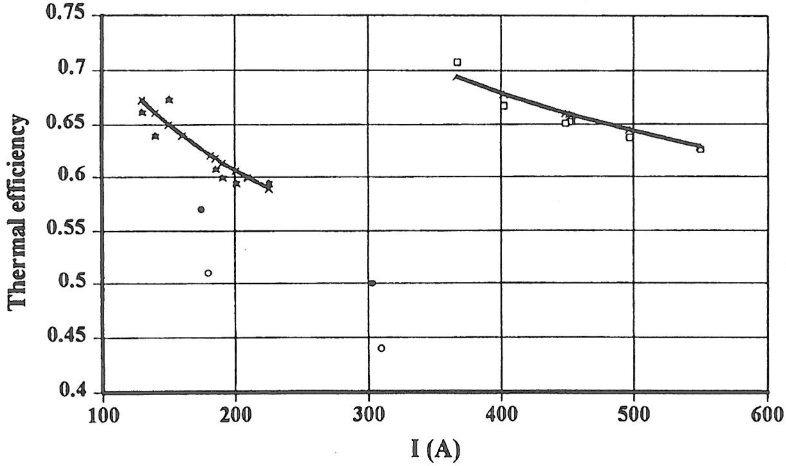


Figure 3. Evolution of thermal efficiency with I for two flowrates of H_2 (★: G=180 slm, □: G= 420 slm) and two Ar-H_2 mixtures (O: 60 slm Ar-30 slm H_2, ●: 60 slm Ar-90 slm H_2). *(button type cathode, 8 mm i.d anode)*

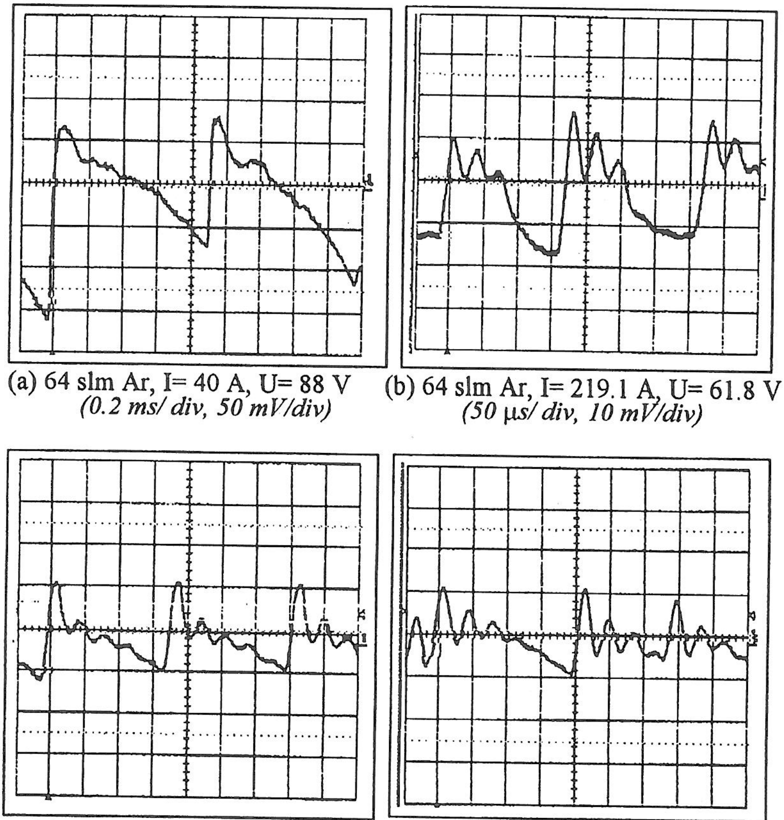
IV. Study of the dynamic behaviour.

For an improvement in the understanding of torch behaviour, it is well known that arc root fluctuations must be taken into account [8]. The arc root attachment at the anode is continuously fluctuating under the influence of the superimposed flow and the MHD forces. The plasma column-anode surface attachment column sometimes called arc loop, is continuously distorted resulting either in a fixed arc spot with short circuits between this column and the wall creating a new arc spot at the wall (restrike mode) in times of the order of 10 μs or in a sliping arc spot with again short-circuits creating a new arc spot which starts to slip along the wall [11, 12, 13,4]. These deformations generate highly transient details in the arc voltage. They were recorded with a fast numerical oscilloscope and they are shown in fig. 4 for differents conditions. With very low arc current ($r_e \sim 1.2$ mm) the recorded signal for Ar (see fig 4.a) is increasing smoothly up to a value where a sudden drop in a few μs is observed (restrike mode). When increasing the arc current ($r_e \sim 2.5$ mm) if the restrike mode with the sudden drop is observed the increase of the voltage with the arc loop length is different. First it is regular (see fig. 4.b) and followed by fast oscillations (with a time step of that of the drop time). At the moment no clear explanations was found for this phenomenon except maybe some "vibrations" of plasma column due to resonnant pressure effect [12] linked both to the difference R-r_e [13] and the plasma viscosity.

Similar phenomena are observed with Ar-H_2 plasmas (see fig. 4.c) and pure H_2 ones (see fig. 4.d), the oscillations being more important in the latter case where the dynamic viscosity is very low.

The Fourier transform of the signal obtained was systematically calculated and a typical example is given in fig. 5. In this case the dominant frequency f corresponding to the restrike mode is about 4.45 kHz.

In previous studies [8] devoted to nitrogen plasmas, it was shown that f was linked both to I (monitoring mainly the value of r_e) and G (modifying the drag force in the column loop both an axial and azimutal directions). If simular results were obtained for Ar-H_2 plasmas, it is not quite the same with pure H_2 for which G had no effect. This is probably due to the weak vortex effect of this gas.



(a) 64 slm Ar, I= 40 A, U= 88 V
(0.2 ms/ div, 50 mV/div)

(b) 64 slm Ar, I= 219.1 A, U= 61.8 V
(50 μs/ div, 10 mV/div)

(c) 64 slm Ar,180 slm H_2
I= 273 A, U= 149 V
(50 μs/ div, 0.5 V/div)

(d) 180 slm H_2, I= 253 A, U= 173 V
(50 μs/ div, 0.5 V/div)

Figure 4. Examples of arc voltage signals recorded with the digitizing oscilloscope. *(The polarity was reversed during the recording and yhe signals should be read from right to left)*

Nevertheless, an evolution of f with the increase of I for a constant value of G was observed. To characterize it, the dimensionless number Sf introduced previously [14] :

$$Sf = \frac{fd^2 \sqrt{\sigma_0 . \mu_0}}{I}$$

was used and a correlation(see eq. 4) was calculated between Sf, Si and Re to characterize the dynamic behaviour of the torch with hydrogen as plasma forming gas:

$$Sf = 3.04.10^{-4} Si^{-0.168} . Re^{-0.131} \quad (4)$$

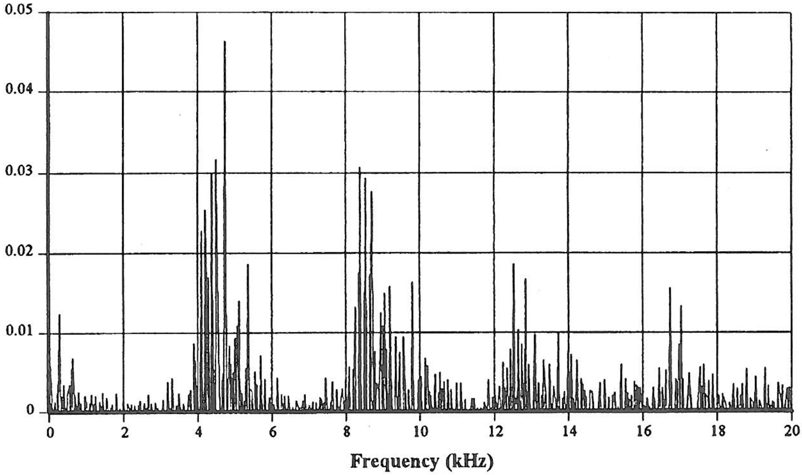


Figure 5. Example of a frequency spectrum (FFT) for an Ar(60 slm)-H_2(30 slm) plasma, I= 179 A.

Figure 6 presents the increase of f with I. As observed previously for nitrogen and air, but with a less marked tendency for hydrogen due to the weak variations of r_e with I, f (i.e the number of disruptions) increases with I. For a constant value of I, f is lower than the value obtained with Ar-H_2 mixture for which the value of r_e is higher (see table 1).

Sf is almost independant of G ($G^{0.037}$).

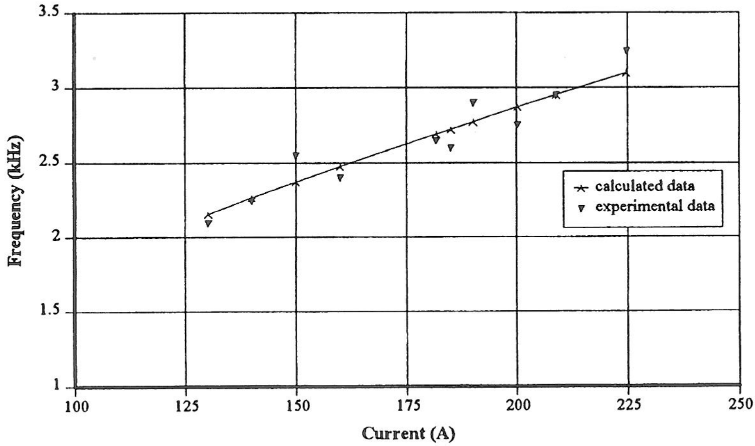


Figure 6. Evolution of the frequency with arc current for a hydrogen plasma (180 slm). *(button type cathode, 8 mm i.d anode)*

V. Conclusion

This study has shown that it was possible to run a D.C vortex plasma torch with a button type cathode and a constant i.d. anode nozzle (8mm) with pure H_2 plasmas in stable operating conditions with a low electrode erosion, provided the hydrogen volumetric flow rate G was increased drastically (at least 3 times) compared to that necessary to run the torch with pure Ar or Ar-H_2 mixtures. This is due to the drastic reductions both of the electrical radius of the arc (very sensitive to I and weakly depending on G) and of the kinematic viscosity diminishing strongly the vortex efficiency. It was also possible to find for the hydrogen plasma dimensionless relationships allowing to calculate the static characteristics (voltage and thermal efficiency with I and G) as well as the dynamic behaviour of the arc root (frequency f of the disruptions plasma column -anode wall). Contrarily to what was observed for Ar or Ar-H_2 plasmas, for H_2 f was depending on I only and almost not on G probably due to the poor vortex efficiency.

References

[1] BRILHAC J.-F. *et al,* Journal of High Temperature and Chemical Processes, 1(3), (1992), 557-562.
[2] YASK'O O.I, Brit. J. Appl. Phys., 2(2), (1969) 733-751
[3] JESTIN L., PATEYRON B., FAUCHAIS P., "Dimensionless study of experimental pressure related behaviour for two powerful vortex blown arc and vortex-stabilized power plasma torches.", High Temp. Dust Laden Jets, Solonenko and Fedorchenko(Eds), (Pub.)VSP, NL.(1989), 211
[4] M.F ZHUKOV, "Electrical arc plasmatrons", Pub. the U.S.S.R Academy of Sciences NAUKA , 630090 Novossibirsk-90, Ed. Pr Mavki 1 (1977)
[5] ZHUKOV M.F, "Linear direct current plasma torches", Thermal Plasma and New Materials Technology, O.P Solonenko and M.F Zhukov, Cambridge Interscience Publishing, 1, (1993), 9-43
[6] JESTIN L., SCHMITT G., " Diagnostics dynamiques internes à des générateurs à plasma", Journal of High Temperature and Chemical Processes, 1(3), (1992), 511-516.
[7] BRILHAC J.-F., PATEYRON B., COUDERT J.-F., FAUCHAIS P., BOUVIER A, JESTIN L. "Static and dynamic behaviours of a DC vortex plasma torch with a hot button type cathode.", 11th ISCP , Loughborough (England), 22nd - 27th August 1993, John Harry (Ed), 1, (1993) 374-379.
[8] BRILHAC J.F., PATEYRON B., DELLUC G.,COUDERT J.-F., FAUCHAIS P., "Study of the dynamic and static behaviours of a D.C vortex plasma torches- Part 1: Button type cathode, accepted in Plasma Chemistry and Plasma Processing (1995)
[9] B. PATEYRON, M.F ELCHINGER, G. DELLUC, P. FAUCHAIS, Plasma Chemistry and Plasma Processing, 12(4), (1992),421-448
[10] STINE M.A, WATSON V.R, The theoretical enthalpy distribution of air in steady flow along the axis of a direct current electric arc, NASA, TN D-1331(1962)
[11] WUTZKE S.A, PFENDER E, ECKERT E.R.G, AIAA J. 5(4) (1968) 707-714
[12] NEUMANN W, Beitr. Plasma Physik 16(1976), 97-109
[13] COUDERT J.F., PLANCHE M.P., BETOULE O., FAUCHAIS P., High Temp. Chem. Processes, 3(6), (1994) 639-652
[14] BRIHAC J.F., "Contribution à l'étude statique et dynamique de torches stabilisées par vortex", Thesis of University of Limoges (France), (1993)