RF multiflux plasmatron study.
Experimental measurements and modelling.

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Abstract

The multiflux RF water cooled plasma torch operating at 25 kW with a generator of 5 MHz allows us to measure the energy balance of the plasma process. The modifications of each experimental parameter can reach to a large variation of the transport properties of the plasma that is to say its energy density and its power induced with a simultaneous modification of the thermal and velocity gradients. The aim of this work is to present the results of the calculation with a modelling taking into account the experimental results and the geometry of the plasma torch used.

I Introduction

The experimental results obtained in previous work indicate that the efficiency of the process (energy going outside the water cooled plasma torch over the energy consume on the network) depends on the power applied, the gas flow rates and the chemical composition [1].

The details of the results show that up to 50% of the energy dissipated can be lost in the generator (triode), in the electrical connexions, in the water cooled coil and in the water cooled copper fingers of the torch by radiation, convection and conduction. It is possible to reduce the energy lost in the inner wall by means of the optimisation of the gas flow rates in axial and sheath flow. But when a diatomic gas is introduced in argon, the dissociation of the molecule leads to energy consumption, and, even if it is introduced in argon in low content, the properties are quite differents. Experimental results are presented for different power applied in the case of pure argon plasma and with a mixture of argon and hydrogen introduced as axial gas or sheath gas (Tables 1 and 2). The bases of the modelling of the RF torch are developed by S.Dresvin [2-3]. Lot of research team used this knowledge in other papers [4-7]. The aim of this work is to correlate the experimental measurements with the results of the calculations of the model.

II Mathematical modelling of a multiflux inductively coupled plasma

The mathematical model is based on the following basic assumptions [2-3] :
- Axially symetric system of coordination with steady state laminor flow with negligible viscous dissipation
- 2-D aximetric temperature, flow and concentration fields
- 2-D electric and magnetic fields
- Optically thin plasma with radiative energy losses

Pur argon plasma

Applied Power (kW)	Intensity (A)	Voltage (kV)	Q_1 (l/min) axial	Q_2 (l/min) sheath	Energetic balance*(η%)
16,2	2,7	6	40	20	34
14,4	2,4	6	50	40	39,5
22,5	3,1	7,2	60	20	37,2
18,3	2,8	6,5	70	20	36
16,2	2,7	6	30	40	37,3
18	3	6	20	40	30,1
21,7	3,1	7	10	60	29,2
16,9	2,6	6,5	45	45	36,4

$$* \eta = \frac{\text{energy going outside the plasma torch}}{\text{energy network}} = \frac{Pu}{P}$$
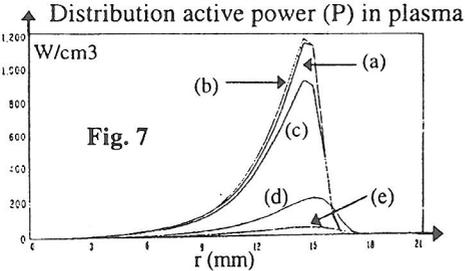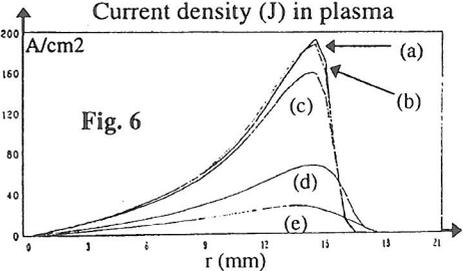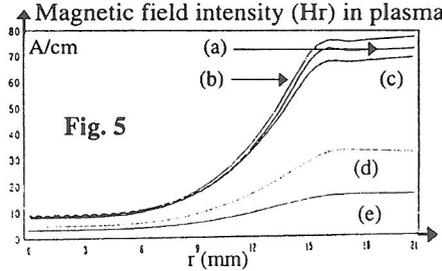
Mixture of Ar-H$_2$ plasma

Applied Power (kW)	I(A)	V(kV)	Axial flow		Sheath flow		η%
			Q(Ar)	Q(H$_2$)	Q(Ar)	Q(H$_2$)	
18,9	2,7	7,0	40	/	19,4	0,6	26,5
15,2	2,3	6,6	40	/	18,2	1,8	32,4
16,2	2,45	6,6	39,4	0,6	20	/	28,4
13	2	6,45	36,8	1,2	20	/	26,7
15,4	2,3	6,7	59,2	0,8	30	/	26,25
13,2	2	6,6	58,4	1,6	30	/	25,7
15	2,2	6,8	60	/	28,4	1,6	29,2

Table 1 and 2 : Experimental results of energetic balance of the plasma process [1]

The plasma confinement tube and the dimensions was included in the computation domains. A schematic of the induction torch considered with its principal dimensions are given in figure 1. The 2-D formulation considers the interaction between the applied magnetic field of the plasma and the effect of the coil geometry of the electromagnetic field.

The continuity, momentum, energy and vector potential equations are given in the following.
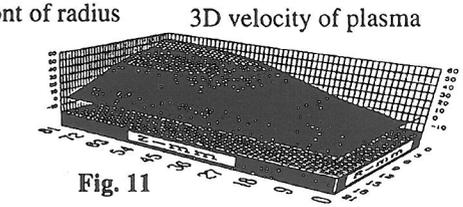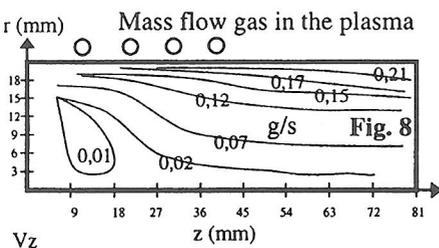
Continuity $\qquad \nabla . \rho . \bar{u} = 0$

Momentum $\qquad \rho . u . \nabla \bar{u} = -\nabla p + \mu \nabla^2 \bar{u} + F$

Energy $\qquad \rho . \bar{u} . \nabla h = \dfrac{\lambda}{C_p} \nabla^2 h + Q - R$

Vector potential $\qquad \nabla^2 . A_\theta = \mu_0 . \sigma . \dfrac{\partial A_\theta}{\partial t}$

Potential vector (Aθ) in plasma

1e-06 Tl.m

Fig. 3

(a)
(b)
(c)
(d)
(e)

r (mm)

Electric field intensity (E) in plasma

V/cm

Fig. 4

(a)
(b)
(c)
(d)
(e)

r (mm)

Magnetic field intensity (Hr) in plasma

A/cm

Fig. 5

(a)
(b)
(c)
(d)
(e)

r (mm)

Current density (J) in plasma

A/cm2

Fig. 6

(a)
(b)
(c)
(d)
(e)

r (mm)

Distribution active power (P) in plasma

W/cm3

Fig. 7

(a)
(b)
(c)
(d)
(e)

r (mm)
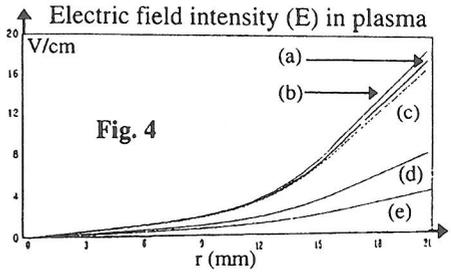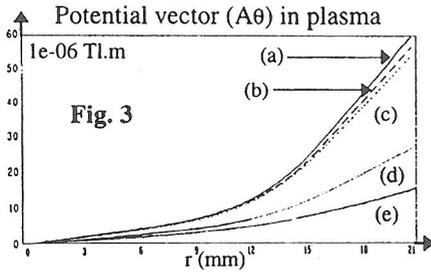
Radian electrical and magnetic properties in the plasma

(a)→ z=12mm (b)→ z=24mm

(c)→ z=36mm (d)→ z=60mm

(e)→ z=81mm

Experimental conditions
U1= 6kV, I1= 154A, F= 5e+06Hz
G1= 20l/min, G2= 40l/min

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r (mm)

Mass flow gas in the plasma

0,21
0,17
0,12 0,15
0,07   g/s   **Fig. 8**
0,01   0,02

z (mm)

r (mm)

Temperature (T) of plasma

300K
11 000K   **Fig. 9**   10 500K
900K
10 000K

z (mm)

Vz

Axial component (Vz) of plasma in front of radius

m/s

(e)
(d)
(c)
(b)
(a)

Fig. 10

r (mm)

3D velocity of plasma

Fig. 11

1745
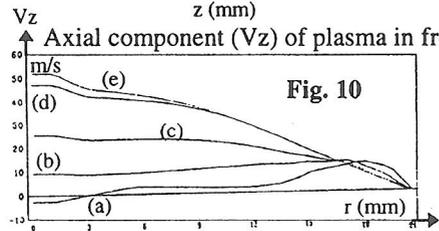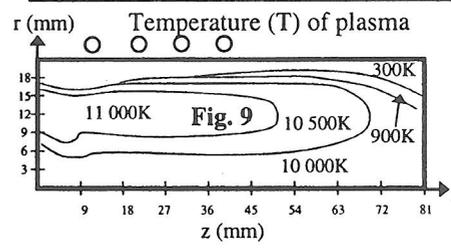
The development of the vector potential model for the electromagnetic field in a radiofrequency plasma is essential if we want to make calculation under frequency close to 5 MHz. Then the frequency was no longer a limiting factor.

The electromagnetic field is coupled to the flow field through Joule heating and Lorentz forces. They are calculated by the following relations:

$$\mu_0 H_z = \frac{1}{r}\frac{\partial}{\partial r}(r.A_\theta) \qquad F_r = \frac{1}{2}\mu_0.\sigma.\text{Real}[E_\theta.H_z^*] \qquad E_\theta = -i.\omega.A_\theta.$$

$$\mu_0 H_r = -\frac{\partial}{\partial z}(A_\theta) \qquad F_z = -\frac{1}{2}\mu_0.\sigma.\text{Real}[E_\theta.H_r^*] \qquad Q = \frac{1}{2}\sigma.[E_\theta.E_\theta^*]$$

where $\bar{u}$ is the velocity vector, μ is the viscosity, F_z and F_r are the axial and radial Lorentz force, h is enthalpy, λ is the thermal conductivity, C_p is the specific heat at constant pressure, p is the pressure, ρ is the density, Q is the Joule heating, R is the volumetric radiation, A_θ is the vector potential, E_θ is the electric field, H_z and H_r are the axial and radial magnetic fields, μ_0 is the permeability of the free space, ω is the pulsation, σ is the electrical conductivity.
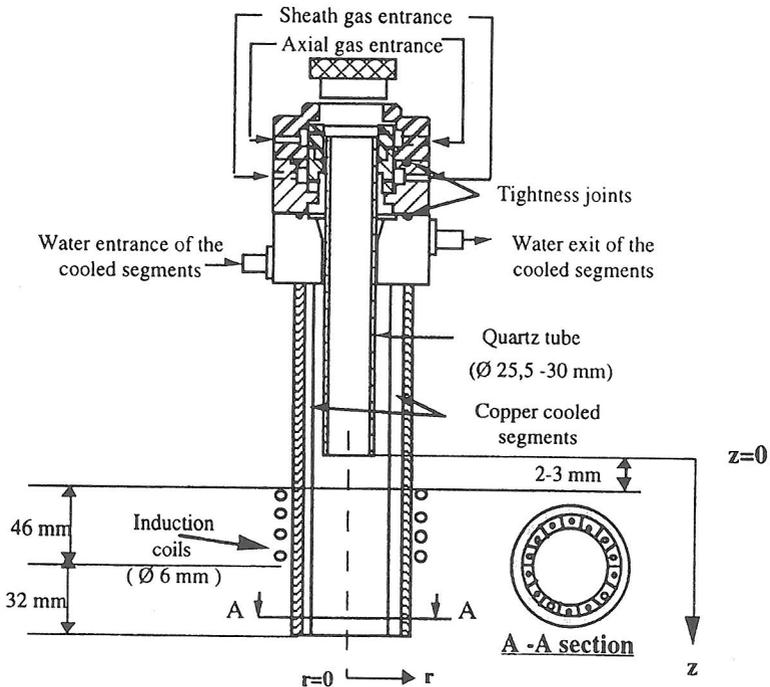

Fig.1 : Water-cooled copper fingers plasma torch

Our approach to modeling these equations and boundary conditions can be found in [5]. The calculation under our particular conditions are determined in different regions in the induction plasma torch. The governing equations with their appropriate boundary conditions were discretized and solved using the SIMPLER algorithm

developed by Patenkar [8] which is a finite difference scheme. An uniform grid system of $(z,r) = (80,30)$ points is used in the calculation.

III Results and discussion

Informations given by CFEI compagny from France indicate that in our case it is possible to determine the intensity and the voltage at the two extremities of the four turns coil (Icoil and Ucoil) starting from those dial by the generator (IA and UA). The formulas used for pure argon plasma and a mixture of argon with 5% of hydrogen are given in the table 3. The dimension and the operating conditions used are indicated on the figure 2.

	pure argon	argon + 5% hydrogen
current intensity	Icoil = 30 . IA	Icoil = 35.IA
voltage of coil	Ucoil = 50% UA	Ucoil = 55% UA

Table 3 : Correspondance between characteristics of current applied on the triode and those applied to the coil
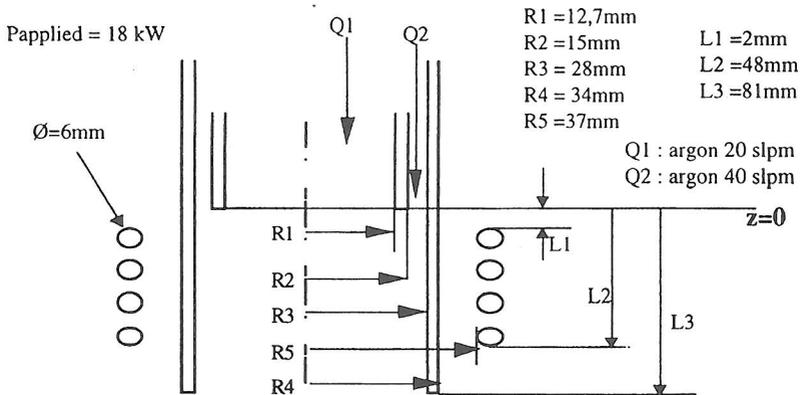

Fig.2 : Schematic diagram with dimension for calculation

The calculations were done with a pure argon and constant flows rate fixed at 20l/min for the axial gas and 40 l/min for the sheath gas. The contribution of the plasma radiation to the wall flux is considered by assuming that 20% of the total radiation emited by a cylindrical slice of plasma is absorbed by the wall. The results concerne the space situated between the point where the two gas flow can be mixed since they are not separated by the intermediate quartz tube till the exit of the metallic wall torch. The velocity, temperature and mass flow gradients in the plasma are due to the radial value of the electrical and electromagnetic fields which are calculated at different axial distances: 12, 24, 36, 60 and 81mm (Fig. 3-7).

The angular potential vector A_θ (Fig. 3) and the angular electric field E_θ (Fig. 4) in the plasma depend on the current frequency (5 MHz). Obviously the calculations lead to a same profil with a continuous decreasing of the value from the wall up to zero along the axis of the plasma whatever is the distance z. Moreover the radial gradients

are the same at the different level of the coil and become smaller and smaller upstream. For a distance z the radial magnetic field intensity (Fig. 5) in the plasma is constant on a thickness at 6mm on the annular part of the plasma flow, then it decreases continuously. These profils are the same whatever is the distance in the coil.

The previous calculations define the radial current density (Fig. 6) and the radial power density (Fig. 7) in the plasma. We can see that the active power is concentrated in a ring having radius of 12/16mm and centred in the axis. The profil of the active density power induced in the plasma is largely due to the radial profil of the current density. At a radius of 15mm the active density power decreases from $1,2kW/cm^3$ in the coil up to $50W/cm^3$ in the exit of the plasma torch. The calculation shows that the active power induced in the axis of the torch is zero. Nevertheless the energy transport occurs under the influence of the flow gas. The main fraction of the gas (Fig. 8) flow along the inner wall of the cooled copper torch since the temperature is smaller and the mass flow of the sheath gas is the two time higher than the axial one.

Considering that the temperature of the inner copper wall stay at 300K by means of the water cooled there is a high radial gradient up to the ring area with an increasing up to 11 000K. In the axial flow the temperature is smaller and equal to a constant value 10 000K (Fig. 9). The axial component of plasma velocity profiles show that between the entrance and the exit of the torch the gas is accelerated up to 50m/s (Fig. 10-11). The plasma temperature of the axial zone lead to a high increasing of the viscosity and a difficulty for the cold gas to penetrate in the plasma. This explain the negative velocity in the upper part of the coil.

IV Conclusion

In a next future, we will take into account the nature of the water cooled wall (copper) and the water flowing in the fingers. The calculation of the properties of a plasma gas with argon and hydrogen will be compared with the experimental results.

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