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STUDY OF A MICROWAVE PLASMA TORCH FOR GAS HEATING

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Among the different types of microwave plasma torches, the axial injection torch (AIT) [1] has been used for several years to create chemically active species, in applications such as gas analysis, surface processing, and gaseous waste treatments [2]. Here, we intend a different kind of application, aiming the heating of helium in a dirigible balloon to achieve its rise in altitude.
Our study is about both experiment and modeling of the AIT, to understand the distribution of its electromagnetic field, the flow of the gas / plasma system, and the heat transfer from the plasma to the gas.

Figure 1 presents a schematics of the experimental set-up used here. The configuration in study consists of a dielectric tube (~30 cm length and ~1-2 cm in diameter) coupled to the AIT's nozzle (see Fig.1). Helium is injected at atmospheric pressure into the AIT (with flow rates of a few L/min), producing a high luminosity, high density plasma [3] (~1 cm length and 1 mm radius) at the nozzle's exit, by coupling of microwave power (500-900 W) at 2.45 GHz frequency.

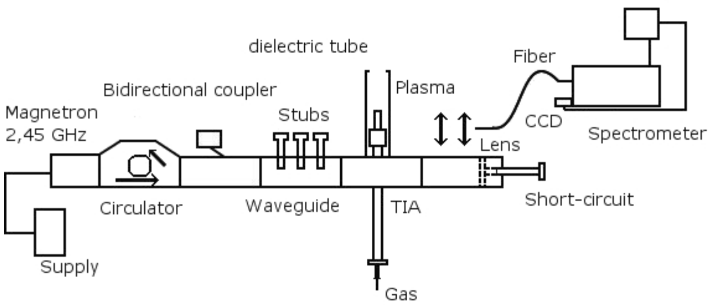

Fig.1: Schematic representation of the experimental set-up

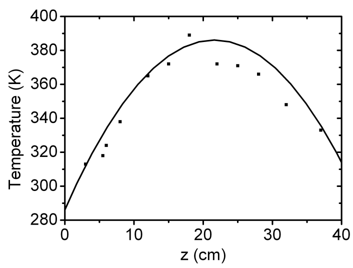

Fig.2: Temperature profile of the tube wall, at 7L/min flow and 500W input power. The points are from measurements and the line is a fit.

The modeling of this AIT wants to describe the gas / plasma system produced within the dielectric tube, in terms of its density, velocity and energy, by coupling three calculation modules:
- electromagnetic (EM-3D), which solves Maxwell's equations considering the permittivity of the different media;
- hydrodynamic (HD-2D), which solves the Navier-Stokes equations for the gas / plasma system;
- plasma (P-1D), which solves the fluid-type equations for the plasma electrons and ions.

The electromagnetic and the hydrodynamic features of this problem have been analyzed in previous works, for a closed reactor configuration [4]. Here, we have developed EM and HD modules using the commercial software COMSOL Multiphysics®.

Our study focuses particularly on the hydrodynamic aspect, to control the distribution of mass density ρ, flow $\rho\vec{v}$ and temperature T_g of the neutral gas particles, in the presence of a plasma heating source, by solving the corresponding mass, momentum, and thermal energy balance equations for helium:

$$\vec{\nabla}\cdot(\rho\vec{v})=0$$
$$\rho(\vec{v}\cdot\vec{\nabla})\vec{v}=-\vec{\nabla}p-\vec{\nabla}\cdot\vec{\tau}$$
$$-\vec{\nabla}\cdot\left(\lambda_g\vec{\nabla}T_g\right)+\rho C_p\left(\vec{v}\cdot\vec{\nabla}\right)T_g-\vec{v}\cdot\vec{\nabla}p=3\frac{m_e}{M_g}n_e\nu k_B\left(T_e-T_g\right)$$

where $p=\left(\rho/M_g\right)k_BT_g$ is the gas pressure, $\vec{\tau}=-\eta\left[\vec{\nabla}\vec{v}+(\vec{\nabla}\vec{v})^T-\left(2/3\right)\vec{\nabla}.\vec{v}\vec{I}\right]$ is the viscosity tensor, η is the viscosity coefficient, C_P is the gas heat capacity at constant pressure, λ_g is the thermal conductivity, M_g is the gas mass, m_e is the electron mass, k_B is the Boltzmann's constant, ν is the electron-neutral collision frequency, and n_e and T_e are the electron density and temperature, respectively (here, these plasma parameters are imposed in the calculations). The terms in the third equation account for the different phenomena leading to an energy exchange of the gas: conduction, convection, the work of pressure forces (left hand-side), and elastic collisions responsible for a plasma-to-gas power transfer (right hand-side). Work is in progress to further include the effect of the ions upon the gas flow.

Experiments have a double purpose: to obtain input data for the model and to validate its results. A thermal probe was used to measure the temperature of the tube wall (see Fig. 2), whose profile was adopted as boundary condition to the hydrodynamic module. Optical emission spectroscopy diagnostics allow obtaining the electron density and temperature (by measuring the Stark broadening of the H_α and H_β atomic lines), and the gas temperature (by fitting the ro-vibrational spectra emitted by the second positive system of N_2, using the software SPECAIR [5]), at various positions along the plasma axis (top, middle and bottom). The plasma is imaged onto the entrance slit of a spectrometer with a 46 cm focal length, equipped with a 1200 lines mm^{-1} grating; a CCD camera is placed at the exit of the spectrometer (see Fig.1). The spectral band detected by this optical device ranges from 200 to 1000 nm. Preliminary measurements yield $n_e \sim 5x10^{14}$ cm^{-3}, $T_e \sim 2x10^4$ K, and $T_g \sim 3x10^3$ K.

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