

Plasma parameters of a small microwave discharge at atmospheric pressure obtained by probe diagnostics

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Abstract. We present the design of a system for probe diagnostics and the results obtained for the plasma parameters in a small portable microwave plasma source operating at atmospheric pressure. The average electron temperature and the argon plasma density in the discharge are estimated from the current-voltage (I-V) characteristics of an asymmetric double probe. The calculated value of the electron temperature is $T_e \sim 1.7 \pm 0.3$ eV. Three models for the probe ion saturation current in a flowing plasma at atmospheric pressure are applied to calculating the plasma density. The calculated value of the plasma density varies with the input power $P = 15 - 25$ W and gas flow rate 250 - 350 sccm. The plasma density estimations obtained by the models lie within a wide range and are compared with results from optical diagnostics.

1. Introduction

The environmental and industrial applications of the microwave discharges at atmospheric pressure, such as detoxification of hazardous gases, surface cleaning and modification and air composition control, require the development of simple techniques for rapid control of the plasma parameters. The double probe diagnostics is a method which allows rapid and simultaneous determination of the main plasma parameters - electron temperature and density.

This work presents the design of a system for probe diagnostics and the results obtained for the plasma parameters in a small portable microwave plasma source [1]. This novel surface-wave plasma source creates dense plasma with stable parameters in a ceramic capillary at atmospheric pressure both in continuous and pulsed regimes. The electron temperature and density of the argon plasma in the discharge are estimated from the asymmetric double probe characteristics. A system was developed for precise measurements of the I-V probe characteristics in continuous and pulsed regimes of the discharge. The acquisition system is based on averaging over many periods of the ramp generator or a fixed number of probe characteristics in a single pulse with controlled time delay with respect to the start. Smoothing and differentiation procedures are applied to the averaged probe characteristics. The electron temperature is obtained by the standard formula, while the plasma density is estimated using the ion saturation current of a small cylindrical probe positioned in the middle of the plasma column and applying the three theories for a probe in a high pressure flowing plasma. These are the "sheath-convection" regime [2], collisional plasmas with high Peclet number [3], and Chung theory for a probe in flowing plasmas [4]. The results obtained for the plasma density value are in a wide range; we

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compared them with results from optical emission spectroscopy. The single probe at recombination regime [5] can also be applied for determining the plasma parameters in a microwave atmospheric plasma jet if a reference electrode is available.

2. Experimental set-up and diagnostics

The experimental set-up is presented in figure 1. Microwave power at frequency $f = 2.45$ GHz supplied by a generator MPG-4M (0-120 W) is fed to the source by a flexible coaxial line through a double directional coupler Pasternack PE2219-30 and a triple stub Maury 1878C. The forward and reflected power are measured by a HP 437B power meter. This low power source is built by pieces of semi-rigid coaxial lines. The exciter of the surface waves is an open coaxial line with outer copper conductor with a diameter of 2 mm and inner conductor – a steel capillary with a diameter of 1 mm. The dielectric of the line is a ceramic tube with an inner diameter of $D=2.R = 1$ mm and an outer of 2 mm of alumina with $\epsilon_d=9.3$. This thin tube is also used as a discharge tube, because the ceramics can with-stand high gas temperatures and has high thermal conductivity and small losses. This material reduces significantly the exciter dimensions l to the length of 10 mm ($l \sim \lambda_0/4 \sqrt{\epsilon_d}$, λ_0 – wavelength in free space). A discharge ceramic tube longer by 11 mm than the exciter is used. The initial tuning of the source at frequency 2.45 GHz is carried ou by a network analyzer HP8757A (S_{11} - measurements). The neutral gas is fed to the discharge tube through the steel capillary. The gas flow (150 - 350 sccm) is measured by a mass-flow controller APEX-AX-MC. The working gas is argon.

The efficient working regime of the source is ensured by additional matching to the generator by using a triple stub. Thus, the plasma source is self-ignited in continuous and pulsed regimes at a specific threshold value of the input power.

The electron temperature and density are estimated from the asymmetric double probe characteristics measured. The first probe is a tungsten cylindrical wire with a length of 0.6 mm and radius of 0.1 mm positioned perpendicularly to the column in the middle of the discharge through a small hole (~0.5 mm) in the tube wall. The second probe is a wire with length of 4 mm and radius of 0.1 mm, positioned inside the discharge tube at its top.

The equipment for optical emission spectroscopy includes a collimating lens, an optical fiber waveguide, Ocean Optics spectrometers and an infrared thermometer.

The probe system used during the experiments consists of several modules presented in figure 2 as a block-diagram. The system applies a ramp-shaped signal to the probe. The “trigger” allows the ramp signal generation to be synchronized (or unsynchronized) with an external source. This option is needed for diagnostics of pulsed discharges. The “ramp generator” produces the desired voltage shape which is

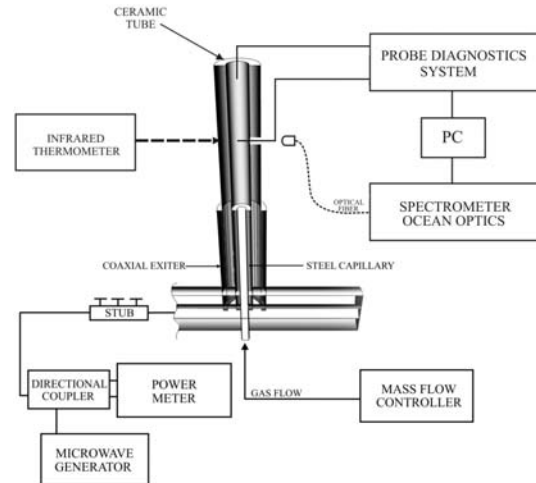


Figure 1. Experimental set-up and diagnostics.

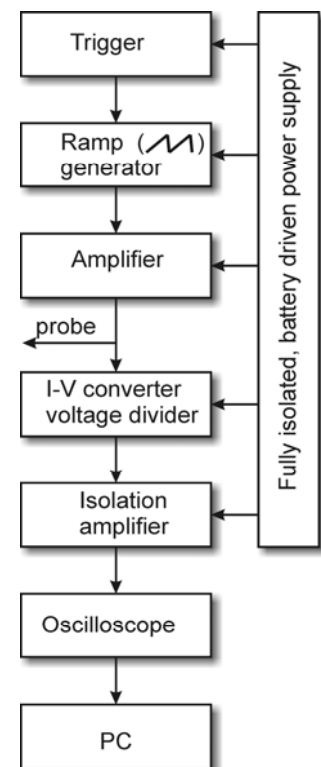


Figure 2. Block-diagram of the probe diagnostics system.

further amplified by the HV amplifier based on an APEX PA78EU operational amplifier. The system allows a large variation of the applied probe voltage parameters: frequency range: 0.1 – 10000 Hz; voltage range: –200 V – +200V; AC peak-to-peak amplitude: from 1 to 200 V; DC level: –200 – +200 V; maximum probe current: 150 mA. The probe current is converted to a voltage signal by the voltage drop over a 30 Ω resistor, while the probe voltage is reduced by a RC voltage divider. The two voltage signals are further transferred to an oscilloscope through isolation amplifiers (AD215). The data records in the oscilloscope are then send to a PC for calculation of the plasma parameters. The data acquisition is based on averaging over several periods of the ramp generator, i.e. one period corresponds to a whole probe characteristic and many probe (up to 256) characteristics are averaged to produce the final I-V curve. The system is designed to operate in two modes: continuous and pulsed mode. In continuous mode, it is assumed that the discharge parameters do not change during the probe characteristic acquisition and the final (averaged) data is a result of averaging of up to 256 consecutive probe characteristics. The pulsed mode of the system is intended for use in pulsed discharges. In this case, the ramp generator is triggered by an external signal corresponding to the pulses from the discharge power supply. In this way the probe voltage signal starts with the same phase at the beginning of every discharge pulse and if the frequency of the ramp is high enough, one can record a fixed number of probe characteristics within a single pulse. Consequently, with proper adjustment of the delay and the time span of the oscilloscope, we can average over probe characteristics (in many consecutive pulses), having the same time delay with respect to the pulse start.

3. Evaluation procedure and results

The I-V probe characteristics recorded by an asymmetric double probe at three values of the input power are presented in figure 3. The negative probe current is collected by the small electrode of the probe positioned in the middle of the tube, while the positive current is collected by the electrode positioned at the top of the tube. The distance between the tips of the electrodes of the double probe is about 1.5 -2.5 mm. The probe can measure the average plasma parameters in the region of the plasma column between the electrodes. The asymmetry of the double probe characteristic (figure 3a) depends on the length of the plasma column (absorbed microwave power, gas flow). The probe characteristics obtained are subjected to a smoothing procedure by a Savitzky-Golay filter (figure 3b) and three-point differentiation [5] for calculation of the first derivative of the current with respect to the applied voltage.

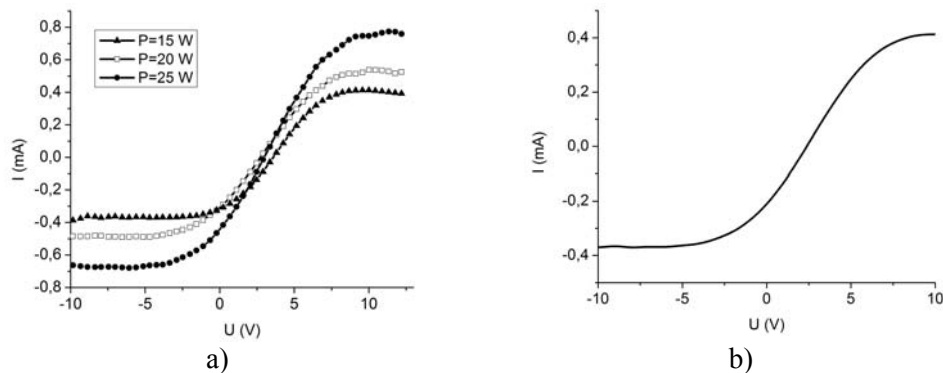


Figure 3. I-V double probe characteristics: a) at 15, 20, 25 W b) smoothed characteristic at 15 W.

The theoretical model [6] of this discharge show that the EEDF is close to Maxwellian at our experimental conditions. The value of electron temperature is obtained from the formula:

$$\frac{kT_e}{e} = \frac{I_{1sat} \cdot I_{2sat}}{I_{1sat} + I_{2sat}} \left(\frac{dI}{dU} \right)^{-1} \Big|_{I=0}$$

where I_{1sat} and I_{2sat} are the ion saturation currents of the electrodes and dI/dU is the first derivative of the probe current at $I = 0$. The calculated value of the electron temperature is $T_e \sim 1.7 \pm 0.3$ eV. Its accuracy depends on many factors, such as the electrode currents fitting curves, the probe characteristics smoothing, the effect of the microwave field, the heating of the probe, etc. The microwave field can cause a distortion in the single probe characteristics and, consequently, overestimation of the electron temperature, but it has a weaker effect on the double probe characteristics. The opposite case of underestimation of T_e due to plasma cooling by the probe was not observed in our measurements.

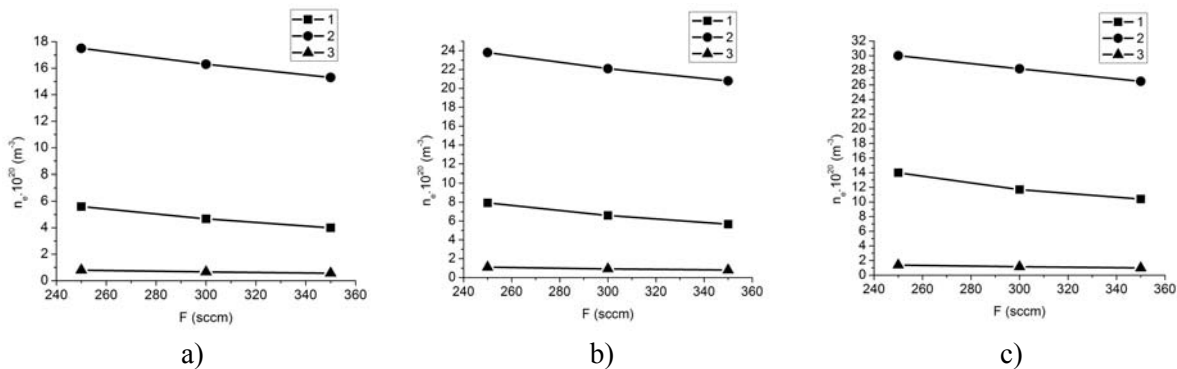


Figure 4. Plasma density obtained by the models 1, 2 and 3: a) at 15 W b) at 20 W and c) 25 W.

Taking into account that the plasma is not isothermal ($T_e > T_g, T_i$) the density was estimated for three power values (figures 4a, 4b, 4c) by the models of collisional plasmas with high Peclet number (model 1), “sheath-convection” regime of ions (model 2) and Chung theory for probe in flowing plasmas (model 3):

$$I_{sat} = - \left(\frac{6.3}{Sc^{0.03}} \right) Pe^{0.4} \cdot e \cdot n_e \cdot D_i \cdot l, \quad 0.5 \leq Pe \leq 20 \quad Pe = v_f \cdot r / D_a, \quad Sc = v_{vis} / D_a, \quad (1)$$

$$I_{sat} = 5.3 (\epsilon_0 \cdot \mu_i \cdot r_p)^{1/4} (n_e \cdot e \cdot v_f)^{3/4} \cdot l \cdot V^{1/2}, \quad \alpha = \lambda_D / 2r_p < 1, \quad \chi = eV / kT_e > 1, \quad Re = \frac{v_f \cdot 2r_p}{\mu_i (kT_i / e)} > 1, \quad Re \cdot \alpha^2 < 1, \quad Re \cdot \alpha^2 \cdot \chi^2 > 1, \quad (2)$$

$$I_{sat} = n_e \cdot e \cdot S \cdot v_f \cdot \sqrt{\frac{l}{Re}} \cdot \left(1 + \frac{T_e}{T_i} \right) \frac{0.293 + 0.181 \cdot Sci}{\sqrt{2} Sci}, \quad Sci = v_{vis} / D_a / n_e, \quad (3)$$

where Pe is the Peclet number, Sc , Schmidt number, D_a and D_i , the ambipolar and ion diffusion coefficients, Re , Reynold's number, l and r_p are the length and radius of the probe, S , the probe surface collecting area, μ_i , the mobility of ions, v_f , the plasma flow velocity and V , the probe voltage. The results show that the plasma density increases with the power applied and decreases with the increase of the plasma flow. The results obtained by optical spectroscopy measurements [7] for $F = 250$ sccm and $P = 20$ W are $T_e = 1.6$ eV and $n_e = 4.5 \times 10^{20} \text{ m}^{-3}$. This demonstrates that the model of “sheath-convection” regime for the probe saturation current gives plasma density values consistent with optical diagnostics.

Conclusions

A probe diagnostics system was developed for measurement of the plasma parameters of a small portable microwave source in continuous and pulsed regimes of operation. The asymmetric double probe technique is applied for determining the average plasma parameters in the middle of the plasma column. The electron temperature was calculated by the standard formula taking into account the factors determining the accuracy. The plasma density was estimated from the ion saturation current by an appropriate model for the specific conditions of the experiment and after calibration with another diagnostics method.

Acknowledgements

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