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Levitation of particles in O_2 plasma

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Oxygen discharges are scientifically and industrially interesting due to their chemical properties and physical effects. The latter are mostly due to the presence of negative ions affecting the plasma boundary in front of the surface to be processed. In this contribution we use particles levitating in the Oxygen plasma sheath as a diagnostic of the intermediate positions in the sheath between the plasma and the solid surface. The experimental results for three particle sizes are compared with the theoretical levitation force obtained by the modelling of the electronegative plasma sheath and the charging of particles in it.

Experiments The plasma was generated by radiofrequency excitation, 13.56MHz and 300V (peak-peak) of the upper of two parallel plane electrodes, the lower electrode being grounded with an external ring biased at -5V to confine electrostatically the particles. These were illuminated by laser-light spread in a thin vertical layer and filmed by a video camera at 90^0. Melamine-formaldehyde particles, of diameter 6.81, 3.42 and 1.29µm were injected in the plasma through a fine mesh from a dispenser at the side edge of the plasma. The experimental arrangement can be found in [1]. Fig. 1 shows the particle position above the electrode. In the intermediate range of pressure 17 < p < 70Pa the particles remained in equilibrium position only for about a minute. In this range two, semi-stable, clearly separate equilibrium layers were detected.

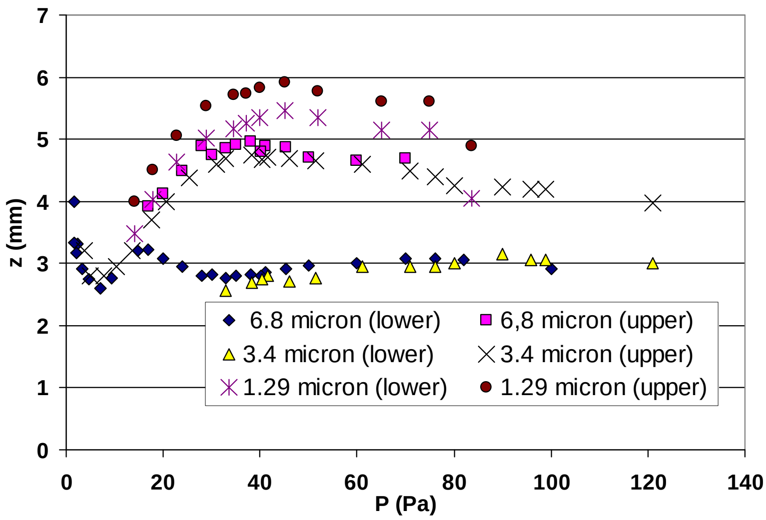

Fig.1 The particle positions above the lower electrode with respect to pressure. There are 2 layers for each size of particles (1.29, 3.4 and 6.8 µm) above 20Pa.

Langmuir probe Lamgmuir probe measurements allowed us to derive the plasma parameters. A W probe, 87.5mm radius and

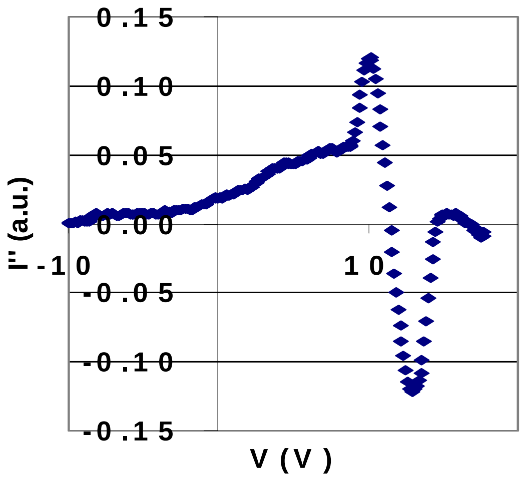

Fig.2 The second derivative of probe current at P=5.6Pa. the 2 peaks shape is caused by the presence of negative ions.

3mm long, was inserted from a lateral port and, being slightly bent, could be rotated to scan the space between the electrodes. The probe was RF actively driven with compensation on the fundamental frequency and the second harmonic. When the electronegativity of the discharge is required, great care must be taken in the data acquisition. The I-V characteristics were averaged on 1000 ramps and the obtained second derivative graphs could be averaged further over 5 sets of measurements. Oxygen gas was constantly introduced in the chamber and the flow rate was increased until the Langmuir probe characteristics were found time independent. The curves were analysed to derive: the electron temperature from the electron retardation part of the characteristic and the electron density from the current at plasma potential. The electronegativity of the discharge, $\alpha = n_-/n_e$ was obtained by the eq.

$$\alpha = \sqrt{\frac{M_-}{m_e}} \frac{\int_{-\infty}^{V_p} \sqrt{|V - Vp|} I''_-(V - V_p) dV}{\int_{-\infty}^{V_p} \sqrt{|V - Vp|} I''_e(V - V_p) dV} \qquad 1$$

where M_- and m are the mass of ion and electron, V is the voltage, V_p is the space potential. I''_e and I''_- denote the second derivative of the current to the probe in a range where it is clearly attributable respectively to electrons and negative ions. The distribution of electrons (depleted at low energies)and negative ions are clearly identifiable only for p < 20Pa, see for example fig. 2. We relay on the conservation of the areas in the unavoidable instrumental integration. This method is valid for non-Maxwellian distributions and not sensitive to the value of the negative ion temperature or to collisions (see table).

P (Pa)	**T_e (eV)**	**n_e (m^{-3})**	**α**	**n_-(m^{-3}) derived**
5.6	**2.3**	**4.7 10^{13}**	**23**	**1.1 10^{15}**
19	**2.7**	**8.5 10^{13}**	**12**	**1.0 10^{15}**
39	**3.3**	**1.4 10^{14}**	**-**	**-**

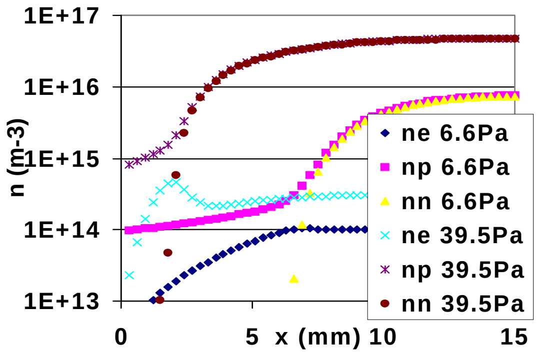

Fig.3 Time-averaged profiles of electron, positive and negative ions densities at P=6.6 and 39.5Pa.

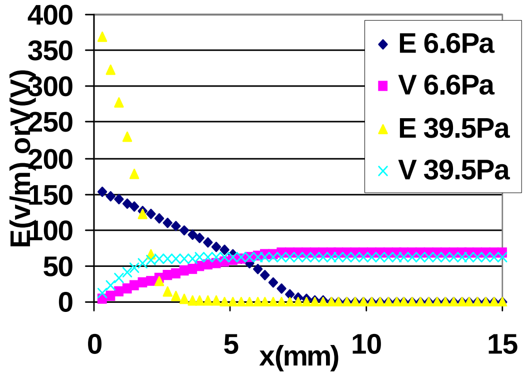

Fig.4 Time-averaged profiles of voltage V and electric field E at P=6.6 and 39.5Pa

Simulation From the particle levitation position, fig.1 and the Langmuir probe results we deduce that for pressures above 20Pa collisional effects are important. The collision-less model presented in [2] explains the higher equilibrium position for the upper layer in the intermediate range of pressures, where the ions have not yet collided, but fails to explain the observed double equilibrium position. Collisions are usually dealt by numerical simulation so we have used the fluid Siglo-RF code (Kinema) [3] for a symmetric RF discharge in O_2, the gap between electrodes being 30mm, the gas pressure p = 6.6Pa and 49.5Pa, and the amplitude of RF voltage $U_{rf\ P\text{-}P}$ = 300 V. We obtained the time-averaged profiles of n_e, n_i, n_n (negative ions), see fig. 3 and the electric field and potential, see fig 4. Particularly interesting is the peak in the electron density at 39.5Pa, at about 2mm from the electrode, due to the radiofrequency. We would expect this peak to be even larger in an asymmetric discharge as in our experiments. The values of α that can be deduced from fig. 3 are somehow higher than the experimentally derived. In plasma environment, with an isotropic distribution of ions, the charge of the particles has been calculated using the vacuum approximation, $Q=4\pi\varepsilon_0 r_p V_f$ with V_f, the floating potentials, derived from

$$n_i e\sqrt{\frac{kT_i}{2\pi M_i}}\left(1+\frac{e|V_f|}{kT_i}\right) = n_e e\sqrt{\frac{kT_e}{2\pi m}}\,e^{-\frac{e|V_f|}{kT_e}} + n_- e\sqrt{\frac{kT_-}{2\pi M_-}}\,e^{-\frac{e|V_f|}{kT_-}} \qquad 2$$

Instead for directed ions we have used the following eq.

$$n_i e\sqrt{\frac{2e|V_o|}{M_i}}\left(1+\frac{|V_f|}{|V_o|}\right) = 4n_e e\sqrt{\frac{kT_e}{2\pi m}}\,e^{-\frac{|V_f|}{kT_e}} + 4n_- e\sqrt{\frac{kT_-}{2\pi M_-}}\,e^{-\frac{e|V_f|}{kT_-}} \qquad 3$$

Here all V are negative numbers, V_0 is measured from plasma and V_f is measured from the local V_0. If collisions are important V_0 should be replaced by the drop of voltage on the last m.f.p. We have used the values of the temperature and density provided by the simulation and $M_- = 16$, $M_i=32$.

The levitation force, F = EQ and the weight of the particles are shown in fig. 5, the lined curves correspond to the sheath solution (eq. 3 for the charge), they overlap continuously to plasma solution (eq.2). The theoretical equilibrium position of the particles is indicated by the crossing of the weight line with the respective levitation force. The larger and medium particles have almost coinciding equilibrium position in the range covered be sheath solution while the smaller particles are clearly in the range where the plasma solution applies. We can not see the double equilibrium position as in fig.1. This may be attributed to the non symmetric set-up of our experiment that may locally amplify the RF enhancement of the charge of the particles. Another reason can be derived from the electron/ negative ion densities given in fig. 3 that give a constant value of α, about 100, for the two pressures. In this case the equilibrium position of the particles would follow the usual shrinking of the sheath at higher pressures. In the experimental case we observe a stronger dependence of α on the pressure. This research was founded by: Das Bundesministerium fuer Bildung und Forschung durch das Zentrum fuer Luft- und Raumfahrt e.V. (DLR) unter dem Foerderkennzeichen 50 RT 0207.

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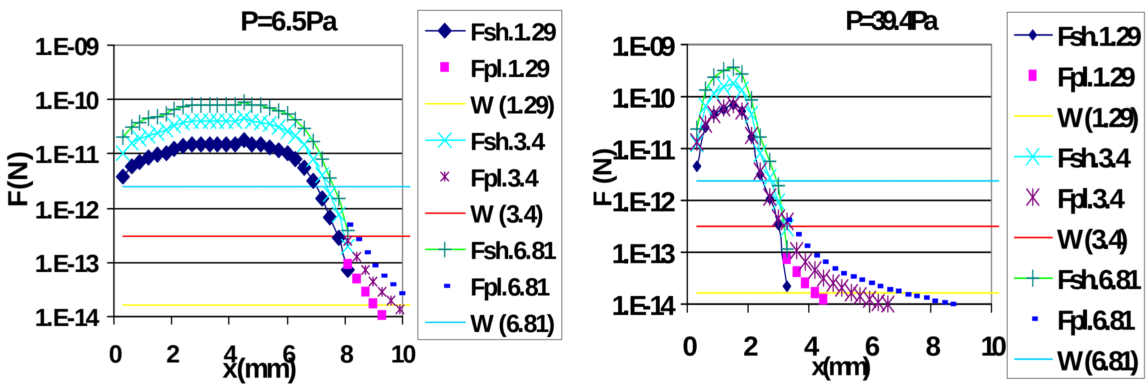

Fig.5 Levitation forces for particles of three sizes from plasma and sheath solution. Horizontal lines define the weight for each particles size.