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LEVITATION OF PARTICLES IN O_2 PLASMA

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Oxygen discharges are scientifically and industrially interesting owing to chemical properties and physical effects. These 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, 13,56 MHz and 300 V (peak-peak) of the upper of two parallel plane electrodes, the lower electrode was grounded with an external ring biased at – 5 V to confine electrosta-tically the particles. These were illuminated by laser-light spread in a thin vertical layer and filmed by a video camera at 90°. Melamine-formaldehyde particles, of diameter 6,81; 3,42 and 1,29 mm 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 $17 < p < 70$ Pa the particles remained in the equilibrium position only for a time of the order of about a minute. In this range two, semi-stable, clearly separate equilibrium layers were detected.

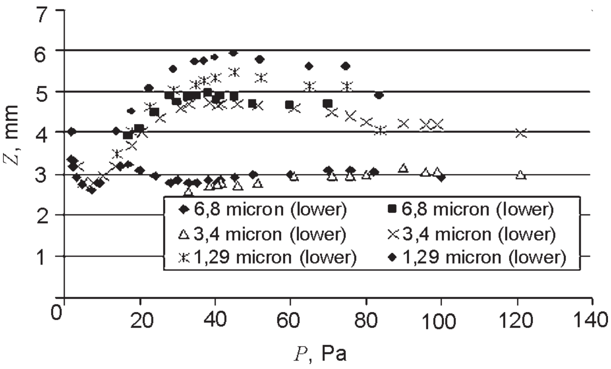

Fig.1. The particle positions above the lower electrode with respect to pressure. There are 2 layers for each size of particles (1,29; 3,4 and 6,8 μm) above 20 Pa.

LANGMUIR PROBE

Langmuir electric probe measurements allowed us to derive the plasma parameters. A W probe, 87,5 mm radius and 3 mm 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 funda-mental 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 ave-raged 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 tempe-rature 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 equation

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

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 and negative ions are clearly identifiable only for $p < 20$ Pa, see for example fig. 2.

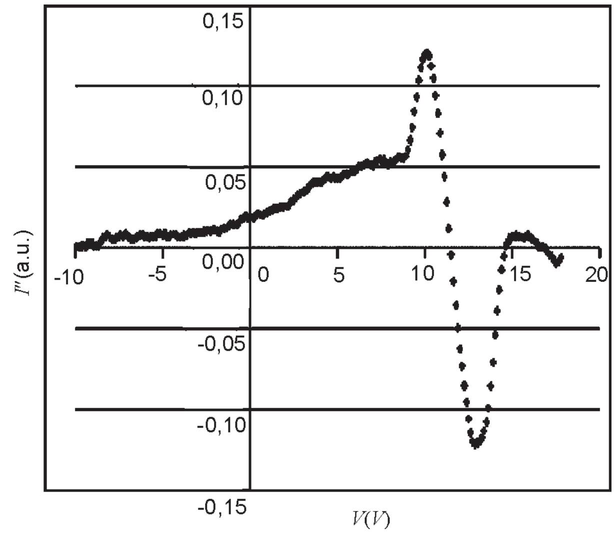

Fig. 2. The second derivative of probe current at $P = 5{,}6$ Pa. The 2 peaks shape is caused by the presence of negative ions.

We will have some error in evaluating the areas in the range in which they overlap but this method is valid for any distribution and not sensitive to the value of the negative ion temperature or to collisions. Some data are given in tabl. 1.

Table 1

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}	25	1,0·10^{15}
39	3,3	1,4·10^{13}	–	–

SIMULATION

From the particle levitation position, fig.1 and the Langmuir probe results we deduce that for pressures above 20 Pa collisional effects are important. These effects are not dealt by the collisionless model presented in [2] so we have tried to explain the experimental results by numerical simulation. We used the fluid Siglo-RF code (Kinema) [3] for a symmetric RF discharge in O$_2$, the gap between electrodes being 30 mm, the gas pressure $p = 6{,}6$ Pa and 49,5 Pa, and the amplitude of RF voltage $U_{rf\,\mathrm{P\text{-}P}} = 300$ 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 39,5 Pa, at about 2 mm 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 is calculated using the vacuum approximation, $Q = 4\pi\varepsilon_0 r_p V_f$ with V_f the floating potentials, derived from:

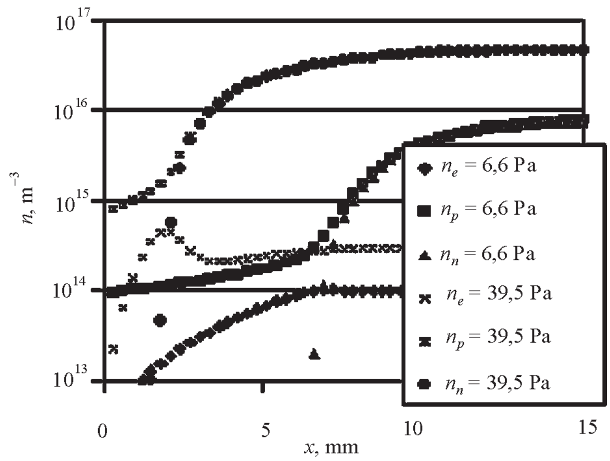

Fig. 3. Time-averaged profiles of electron, positive and negative ions densities at $P = 6{,}6$ and 39,5 Pa.

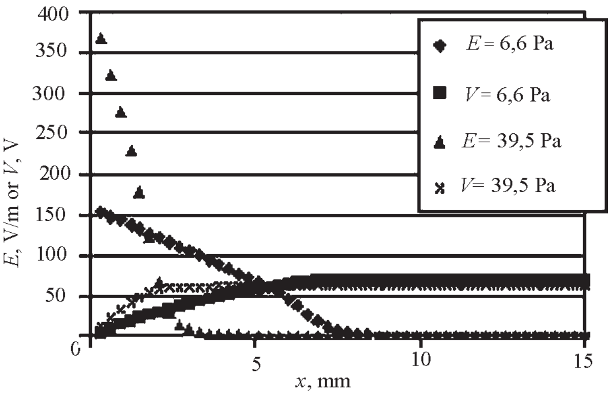

Fig. 4. Time-averaged profiles of voltage V and electric field E at $P = 6{,}6$ and 39,5 Pa.

$$n_i e\sqrt{\frac{kT_i}{2\pi M_i}}\left(1+\frac{e|V_f|}{kT_i}\right)=n_e e\sqrt{\frac{kT_e}{2\pi m}}\exp\left(-\frac{|V_f|}{kT_e}\right)+$$

$$+n_- e\sqrt{\frac{kT_-}{2\pi M_-}}\exp\left(-\frac{e|V_f|}{kT_-}\right). \qquad (2)$$

Instead for directed ions we have used the following eq.

$$n_i e\sqrt{\frac{2e|V_0|}{M_i}}\left(1+\frac{|V_f|}{|V_0|}\right)=4n_e e\sqrt{\frac{kT_e}{2\pi m}}\exp\left(-\frac{|V_f|}{kT_e}\right)+$$

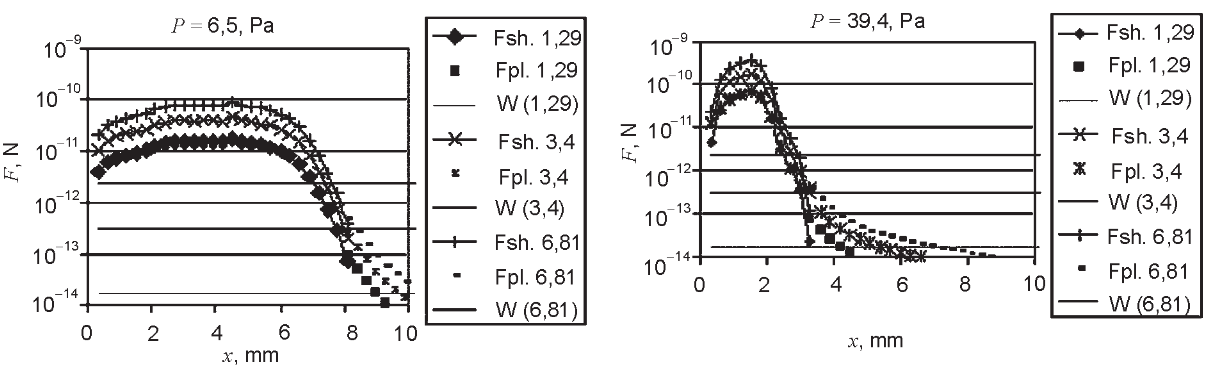

Fig. 5. Levitation forces for particles of three sizes from plasma and sheath solution. The horizontal lines define the weight for each particles size.

$$+4n_{-}e\sqrt{\frac{kT_{-}}{2\pi M_{-}}}\exp\left(-\frac{e\left|V_f\right|}{kT_{-}}\right). \tag{3}$$

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 $M_- = 16$ and $M_i = 32$.

The levitation force and the weight of the particles are shown in figs. 5 and 6; the lined curves correspond to the sheath solution (eq. 3). The theoretical equi-librium 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 while the smaller particles are clearly in the range where the plasma solution applies (eq. 2). We cannot see the double equilibrium position as in fig.1. This may be attributed to the nonsymmetric set-up of our experiment or to some approximation of the code.

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ЛЕВІТАЦІЯ ЧАСТИНОК У O_2 ПЛАЗМІ

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Розряди в кисні представляють науковий і технологічний інтерес завдяки хімічним властивостям та фізичним ефектам. Причиною цього є наявність негативних іонів, що впливають на границю плазми перед оброблюваною поверхнею. У даній роботі використовуються частинки, які левітують в приелектродному шарі кисневої плазми як діагностичний засіб для проміжних положень у шарі між плазмою і твердою поверхнею. Експериментальні результати для трьох розмірів частинок порівнюються з теоретичною силою левітації, отриманої за допомогою моделювання плазмового шару в електронегативному газі та процесу зарядки в ньому частинок.

ЛЕВИТАЦИЯ ЧАСТИЦ В O_2 ПЛАЗМЕ

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Разряды в кислороде представляют научный и технологический интерес благодаря химическим свойствам и физическим эффектам. Причиной этого является наличие отрицательных ионов, воздействующих на границу плазмы перед обрабатываемой поверхностью. В данной работе используются частицы, левитирующие в приэлектродном слое кислородной плазмы как диагностическое средство для промежуточных положений в слое между плазмой и твердой поверхностью. Экспериментальные результаты для трех размеров частиц сравниваются с теоретической силой левитации, полученной с помощью моделирования плазменного слоя в электроотрицательном газе и процесса зарядки в нем частиц.