Argon surface wave discharges at medium pressure. Experiments and discussion on the energy balance

A. Granier, G. Gousset, P. Leprince, J. Marec

► To cite this version:

A. Granier, G. Gousset, P. Leprince, J. Marec. Argon surface wave discharges at medium pressure. Experiments and discussion on the energy balance. *Revue de Physique Appliquée*, 1987, 22 (9), pp.999-1006. 10.1051/rphysap:01987002209099900 . jpa-00245660

HAL Id: jpa-00245660

<https://hal.science/jpa-00245660>

Submitted on 1 Jan 1987

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Classification
Physics Abstracts
52-80

Argon surface wave discharges at medium pressure. Experiments and discussion on the energy balance

A. Granier, G. Gousset, P. Leprince and J. Marec

Laboratoire de Physique des Gaz et des Plasmas (*), Université Paris-Sud, 91405, Orsay Cedex, France

(Reçu le 11 février 1987, révisé le 25 mai 1987, accepté le 26 mai 1987)

Résumé. — On étudie les décharges d'argon, créées par onde de surface à 210 MHz, dans des tubes capillaires entre 10 et 200 Torr. Ces décharges sont caractérisées expérimentalement ; le profil longitudinal de densité électronique, la fréquence de collision effective ν et la puissance moyenne nécessaire au maintien d'une paire électron-ion θ sont étudiés en fonction de la pression. On démontre expérimentalement que θ ne dépend pas de la densité électronique et est minimum entre 20 et 50 Torr. Enfin on développe un modèle énergétique simple. Il décrit bien le comportement de θ en fonction de la densité électronique et de la pression, mettant en évidence le rôle joué par la recombinaison dissociative de Ar_2^+ au-dessus de 100 Torr.

Abstract. — Argon surface wave discharges, created at 210 MHz in capillary tubes have been studied at medium pressure, from 10 Torr to 200 Torr. Such discharges have been experimentally characterized ; the electron density profile along the plasma column, the effective electron neutral collision frequency ν and the mean power needed to maintain an electron-ion pair in the discharge θ have been determined as functions of the pressure. It is experimentally proven that θ is independent of the electron density and exhibits a minimum at approximately 20-50 Torr. Afterwards a simple energetic model is developed. It describes quite well the behaviour of θ with both the electron density and the pressure, indicating the dominating rôle of Ar_2^+ dissociative recombination above 100 Torr.

1. Introduction.

Generation and maintaining of long plasma columns by surface waves, from very low pressure (~ 100 mTorr) up to atmospheric pressure, is a well known phenomenon. Up to now, these discharges have been mainly studied at low pressure ($p \leq 10$ Torr), both experimentally [1-4] and theoretically [5-6].

In spite of their great importance for various applications, such as chemical analysis by optical emission spectroscopy [13-14], medium pressure discharges ($10 \text{ Torr} \leq p \leq P_{\text{atm}}$) have seldom been investigated. Indeed in this pressure range, diagnostics and modelling are difficult to perform.

The aim of this paper is to improve the knowledge of medium pressure discharges. Therefore we have studied argon surface wave discharges in capillary tubes created at 210 MHz from 10 Torr to 200 Torr.

First of all, we report the experimental characterization of such discharges. The axial electron density

profile is measured and discharge characteristics, such as the effective electron neutral collision frequency for momentum transfer ν and the mean power needed to maintain an electron-ion pair in the discharge θ , are determined. Next, medium pressure results are compared with those at low pressure.

Afterwards a simple energetic model, yielding approximate values of θ is exhibited. Finally the influence of both electron density and pressure on the power required to maintain the discharge is discussed, and the results of the model are compared with those of the experiment.

2. Experimental characterization of the medium pressure discharges.

2.1 THE EXPERIMENTAL SET-UP. — The experimental set-up is shown in figure 1. The discharge is created in a capillary quartz tube (internal radius, a , ranges from 1 to 1.75 mm) in argon gas, without flow. The HF power (up to 400 W) is coupled to the argon gas by a surfatron structure [1]. With such a

(*) Associated with the CNRS.

Fig. 1. — The experimental set-up.

launcher, the symmetric azimuthal mode $m = 0$ is preferentially excited. Incident (P_{inc}) and reflected (P_{ref}) powers are measured by a bidirectional coupler. Coupling efficiency $(1 - P_{ref}/P_{inc})$ depends on the pressure and ranges from 60 % (200 Torr) to 95 % (10 Torr).

The surface wave simultaneously propagates and ionizes from the excitation gap to the end of the plasma column. The power carried by the wave, as well as the electron density decrease from the excitation gap to the end of the discharge, where the electron density is equal to a critical value n_e^c , which is an increasing function of the wave frequency.

The abscissa $Z = 0$ is chosen at the end of the discharge and the excitation gap abscissa is $Z = L$, where L denotes the plasma length.

2.2 AXIAL ELECTRON DENSITY PROFILE. — In medium pressure discharges, the electron density ranges from a few 10^{12} cm^{-3} ($Z = 0$), to a few 10^{14} cm^{-3} ($Z = L$). The electron density is difficult to measure over such a range. Thus, the diagnostic generally used in low pressure and low collisional discharges has been modified to enable the electron density diagnostic under our collisional plasma conditions.

Indeed, in low pressure surface wave discharges the effective collision frequency ν is smaller than the excitation pulsation ω . Thus the dispersion relation of the exciting wave $\lambda(n_e)$ is independent of ν . Furthermore, the axial wavelength profile of the exciting wave $\lambda(Z)$ can easily be measured by an interferometer method, which has been accurately detailed previously [4, 7]. Then, the axial electron density profile $n_e(Z)$ is deduced from the dispersion relation $\lambda(n_e)$. Nevertheless, in medium pressure

discharges created at 210 MHz, the electron-neutral collision frequency is much greater than the excitation pulsation (i.e. $\nu \gg \omega$). Then the dispersion curve $\lambda(n_e)$ strongly depends on ν [8], which makes it difficult to determine the electron density from the wavelength of the exciting wave.

Therefore a low power test wave is excited at a frequency f_{test} in the discharge created at the frequency f_0 [8, 9]. We have used a test frequency (2450 MHz) greater than the excitation frequency (210 MHz) so that the ratio ν/ω_{test} is about 1. Furthermore, since the critical density of the test wave is greater than the critical density of the exciting wave, the test wave stops propagating before the end of the discharge, avoiding the development of any stationary wave.

This enables the determination of the electron density from the wavelength profile of the test wave, without taking into account ν/ω ($0 \leq \nu/\omega_{test} \leq 2$), since in our electron density range all the corresponding curves $\lambda(n_e)$ coincide. The axial electron density profile obtained at 100 Torr ($a=1 \text{ mm}$) is plotted in figure 2.

Fig. 2. — A typical electron density profile. $p=100 \text{ Torr}$, $a=1 \text{ mm}$, $P_{inc} = 250 \text{ W}$, $L=50 \text{ cm}$.

2.3 MEAN POWER NEEDED TO MAINTAIN AN ELECTRON. — At a given pressure, $n_e(Z)$ has been measured for various incident powers. Taking the origin at the end of each plasma column, we note that the different axial profiles $n_e(Z)$ are fitting. Thus we can unambiguously define in every plasma slab (defined by its abscissa Z and its thickness ΔZ), the mean power needed to maintain an electron in the discharge $\theta(Z)$. Thus $\theta(Z)$ is equal to :

$$\theta(Z) = P_{abs}(Z, \Delta Z)/N_e(Z, \Delta Z) \quad (1)$$

$P_{abs}(Z, \Delta Z)$ is the absorbed power in the considered slab,

$$P_{abs}(Z, \Delta Z) = P_{inc}(Z + \Delta Z/2) - P_{inc}(Z - \Delta Z/2)$$

$N_e(Z, \Delta Z)$ is the total number of electrons which are contained in this slab

$$N_e(Z) = \Pi a^2 \cdot \int_{Z-\Delta Z/2}^{Z+\Delta Z/2} n_e(\eta) d\eta.$$

Typical results of $\theta(Z)$ are plotted in figure 3 ($p=100$ Torr, $a=1$ mm, and $\Delta Z=10$ cm). θ accuracy is about 20 %. Thus we deduce that θ is almost constant along the discharge, i.e., θ does not depend on the electron density. We conclude that θ can be considered as depending only on the pressure and on the discharge radius. Thus θ is a characteristic of the discharge. This property has previously been pointed out in low pressure discharges [4, 6] but was not expected in medium pressure discharges. The aim of next sections is to explain and discuss this experimental result, using an energy balance in every plasma slab.

Fig. 3. — A typical mean power for maintaining the discharge profile. $p=100$ Torr, $a=1$ mm, $P_{\text{inc}}=250$ W, $L=50$ cm.

2.4 EFFECTIVE COLLISION FREQUENCY. — Until now we have measured the axial profile $n_e(Z)$ and defined a power θ , characteristic of the discharge. If we further assume that the effective collision frequency ν is constant along the discharge, we can easily compute axial electron density profiles $n_e^{\text{th}}(Z)$ depending on ν . Indeed, we can write in any slab (Z, dZ) that the power lost by the wave equals the power needed to maintain the plasma,

$$P_{\text{inc}}(Z) \cdot 2 \alpha_\nu(n_e(Z)) \cdot dZ = \theta \cdot \Pi a^2 \cdot n_e(Z) \cdot dZ \quad (2)$$

α is the attenuation of the surface wave. α is deduced from the wave propagation study [8] and depends on a , ω , ν and n_e . Since a and ω are fixed (for a given discharge), α can be written in the form $\alpha_\nu(n_e)$.

Differentiation of relation (2), taking into account

that $d\theta/dZ = 0$ and assuming ν independent of Z , leads to the following relation [8],

$$\frac{dn_e}{dZ} = \frac{2 \cdot \alpha_\nu(n_e) \cdot n_e}{1 - \frac{d\alpha_\nu}{dn_e} \cdot \frac{n_e}{\alpha_\nu}} \quad (3)$$

which is numerically integrated to provide theoretical electron density profiles $n_e^{\text{th}}(Z)$.

Then we can compare the experimental electron density profile $n_e^{\text{exp}}(Z)$ with theoretical profiles, computed for various values of ν , $n_e^{\text{th}}(Z)$. The best fit of $n_e^{\text{th}}(Z)$ with $n_e^{\text{exp}}(Z)$ leads to the effective collision frequency ν . An example of ν determination is exhibited in figure 4 ($p=100$ Torr, $a=1$ mm, $\nu = 2.6 \times 10^{10} \text{ s}^{-1}$). From this example we deduce that ν is obtained with about 20 % accuracy.

Fig. 4. — Determination of the effective collision frequency, $p=100$ Torr, $a=1$ mm, $P_{\text{inc}}=250$ W, $L=50$ cm. (O) experimental electron density. Calculated electron density profile for various collision frequencies (— · —) $\nu = 1.95 \times 10^{10} \text{ s}^{-1}$, (—) $\nu = 2.6 \times 10^{10} \text{ s}^{-1}$, (.....) $\nu = 3.25 \times 10^{10} \text{ s}^{-1}$.

3. Experimental results versus pressure.

In the previous section we have developed a method to experimentally characterize a discharge. We are now going to study the variation of the discharge characteristics with the pressure. ν and θ variations are plotted in figures 5 and 6. These results have been obtained at medium pressure (10 Torr-200 Torr) in two different tubes ($a=1$ mm and $a=1.75$ mm) and low pressure results [7] have been plotted too.

Such experiments have not been performed above 200 Torr because of the constriction of the discharge (which is experimentally observed). Indeed such a constriction disables the diagnostic of ν and θ . Therefore the uncertainty of ν and θ , is greater at 200 Torr (constriction limit) than at lower pressures.

Fig. 5. — Dependence on the pressure of the collision frequency in several tubes. Values of a (mm), (O), 1 ; (Δ), 1.75. Large symbols are used for medium pressure results.

Fig. 6. — Dependence on the pressure of the mean power θ for maintaining discharges in several tubes. Values of a (mm): (O), 1 ; (Δ), 1.75. Large symbols are used for medium pressure results.

First of all we note that medium pressure results are in fair agreement with low pressure ones. No discontinuity is observed. The effective collision frequency increases with the pressure ; at low pressure ν is nearly proportional to the pressure while at high pressure ν increases only slightly with the pressure.

Moreover, the ratio ν/ω_{test} is smaller than 2 for all pressures. This validates the use of the test wave dispersion curve $\lambda(n_e)$ independent of ν (cf. Sect. 2).

Nevertheless, measurements of θ show a marked difference between low and medium pressures. Indeed, at low pressure, θ strongly decreases as the pressure increases. Then θ reaches a minimum, before increasing with the pressure at higher pressures. The pressure corresponding to the minimum of θ depends on the plasma radius. θ is minimum at :

~ 20 Torr with $a = 1.75$ mm
~ 50 Torr with $a = 1$ mm.

Since θ is the power needed to maintain an electron in the discharge, it obviously depends on the electron loss processes, and a minimum of θ corresponds to a minimum of electron losses.

The study of low pressure discharges has proven that such discharges are governed by ambipolar diffusion [5-6], so that electrons are mainly lost by ambipolar diffusion and recombination on the tube walls. The ambipolar diffusion electron loss frequency decreases as the pressure increases, which explains that θ has the same behaviour at low pressure.

The increase of θ at higher pressures means that another electron loss process occurs which increases the electron loss frequency. We expect this loss process to be volume recombination of Ar^+ or Ar_2^+ .

So the minimum of θ corresponds to a change in the plasma behaviour and occurs when ambipolar diffusion and volume recombination electron losses are comparable.

4. Simple energetic model.

In the previous section we have qualitatively discussed the variations of θ with the pressure. The aim of this section is to make an approximate calculation of θ , enabling us to understand its variations with both the electron density and the pressure.

θ is the energy transferred *per* electron (which takes its energy from the microwave electric field) and *per* second to the surrounding argon gas. This power is transferred either by elastic collisions or by inelastic collisions (excitation and ionization). Our aim is to calculate an approximate value of θ *versus* n_e , p , a , under our experimental conditions. Therefore we shall use a three step method. Firstly we write an exact expression of θ . Next, we shall discuss how to approximate this expression. Finally we shall develop a simple kinetic model, enabling us to obtain approximate values of θ .

4.1 EXACT EXPRESSION OF θ . — From its definition, θ can be written as the sum of three terms, θ_{el} the power dissipated by electron-neutral elastic collisions, θ_{ion} the power transferred by ionization, either by direct or multistep ionization and θ_{exc} the power transferred by excitation to any upper level, without contribution to the ionization.

$$\theta = \theta_{\text{el}} + \theta_{\text{ion}} + \theta_{\text{exc}}. \quad (4)$$

Using the following notations, we can write detailed expressions of θ_{el} , θ_{ion} , and θ_{exc} .

m : electron mass

M : argon mass

T_e : electron temperature

ν : electron-neutral collision frequency

V_j : threshold excitation energy of a particular atomic state j

V^+ : argon ionization potential

n_j : j^{th} excited level density

C : electron rate coefficient with a subscript and an upper subscript denoting respectively the initial and the final states of a transition, (subscript $j=0$ refers to the ground state and upper subscript + means ionization)

ν_j^+ : ionization frequency *per* electron ($= n_j C_j^+$)

ν_q^m : excitation frequency *per* electron ($= n_q C_q^m$)

— θ_{el} can be written as

$$\theta_{\text{el}} = \frac{3m}{M} k T_e \nu \quad (5)$$

where k is the Boltzmann constant

— Whatever the ionization process (direct or multistep) the energy transferred by ionization is equal to eV^+ . In a multistep ionization the energy is transferred by electron collisions to an excited level k followed by an ionization from this excited level, which frequency is denoted ν_k^+ . Finally the total power absorbed by ionization can be written in the form:

$$\theta_{\text{ion}} = eV^+ \sum_{k=0}^{\infty} \nu_k^+ \quad (6)$$

Thus we introduce an effective ionization collision frequency

$$\nu_{\text{ion}}^{\text{eff}} = \sum_{k=0}^{\infty} \nu_k^+ \quad (7)$$

and relation (6) becomes

$$\theta_{\text{ion}} = eV^+ \nu_{\text{ion}}^{\text{eff}} \quad (8)$$

— θ_{exc} is equal to the total energy transferred from any excited level to any upper level *minus* the power involved in a multistep ionization process,

$$\theta_{\text{exc}} = \sum_{q=0}^{\infty} \sum_{\substack{m=1 \\ m>q}}^{\infty} e(V_m - V_q) \nu_q^m - \sum_{k=1}^{\infty} eV_k \nu_k^+ \quad (9)$$

4.2 ESTIMATION OF θ . — The expression of θ involves the excitation and ionization cross sections (involved in the various rate coefficients C) as well as the populations of the various excited levels and the electron distribution function. So the exact calculation of θ requires, on the one hand, the knowledge of all the cross sections and, on the other hand the resolution of a complete collisional radiative model. This model consists in the resolution of the steady state rate balance equation for electrons,

ions, and both excited or ground state atoms. It has been solved at low pressures [5, 6] but not at medium pressure. Indeed at higher pressure many more species (particularly Ar_2^+) and many more processes (particularly three body reactions) have to be taken into account. Moreover many reaction rate coefficients are unknown. Our aim is not to solve such a complex system, but to find approximate values of θ .

First of all, θ_{el} is relatively easy to estimate. Indeed ν is determined experimentally and T_e is about 10^4 K. θ_{el} ranges from 10^{-14} W (at 1 Torr) to 10^{-13} W (at 200 Torr).

Secondly, $\theta_{\text{ion}} = eV^+ \nu_{\text{ion}}^{\text{eff}}$ cannot be easily calculated since it would require a complete collisional radiative model. Nevertheless, since creations and losses of electrons are equal, the effective ionization frequency $\nu_{\text{ion}}^{\text{eff}}$ *per* electron is equal to the effective electron loss frequency $\nu_{\text{loss}}^{\text{eff}}$ *per* electron

$$\nu_{\text{ion}}^{\text{eff}} = \nu_{\text{loss}}^{\text{eff}} \quad (10)$$

and

$$\theta_{\text{ion}} = eV^+ \nu_{\text{loss}}^{\text{eff}} \quad (11)$$

So we shall calculate $\nu_{\text{loss}}^{\text{eff}}$ instead of $\nu_{\text{ion}}^{\text{eff}}$, since it involves rather well-known processes (i.e. diffusion and volume recombination).

On the other hand θ_{exc} cannot be estimated, since it can only be written in the form (9), implying the resolution of a complete collisional radiative model.

In conclusion, our aim is now to estimate θ_{ion} , which will enable us to compare the experimental values of θ with the estimated values $\theta_{\text{el}} + \theta_{\text{ion}}$.

4.3 ESTIMATION OF θ_{ion} .

4.3.1 Determination of the electron loss frequency.

— We shall estimate the effective loss frequency taking into account the various loss processes. This study is achieved under the following conditions:

pressure (Torr) : $1 \text{ Torr} \leq p \leq 200 \text{ Torr}$
 electron density (cm^{-3}) : $10^{12} \text{ cm}^{-3} \leq n_e \leq 10^{15} \text{ cm}^{-3}$
 electron temperature (K) : $T_e \approx 10^4 \text{ K}$
 neutral temperature (K) : $1\,000 \text{ K} \leq T_0 \leq 2\,000 \text{ K}$
 plasma radius (cm) : $0.1 \text{ cm} \leq a \leq 0.175 \text{ cm}$

The units used in any numerical expression are given inside the brackets.

Charged particles are lost, either by ambipolar diffusion followed by recombination on the wall, or by volume recombination. Thus $\nu_{\text{loss}}^{\text{eff}}$ can be written as the sum of two loss frequencies ν_A (ambipolar diffusion) and ν_R (volume recombination)

$$\nu_{\text{loss}}^{\text{eff}} = \nu_A + \nu_R \quad (12)$$

The ambipolar diffusion loss frequency can be written in the form (assuming a Bessel radial profile)

$$\nu_A = \left(\frac{2.4}{a} \right)^2 D_+ (1 + T_e/T_+). \quad (13)$$

D_+ is the ambipolar diffusion coefficient which is nearly the same for Ar^+ and Ar_2^+ ions. T_+ is the ion temperature which is assumed to be equal to the neutral gas temperature (indeed the ions are weakly influenced by the electric field). Finally ν_A is equal to

$$\nu_A = 2.2 \times 10^{-3} T_0(T_0 + T_e)/pa^2 \quad (14)$$

or

$$\nu_A = 2.15 \times 10^{16} T_e(1 + T_0/T_e)/n_0 a^2 \quad (15)$$

ν_A mainly depends on the neutral density n_0 , the electron temperature and the plasma radius. Under our conditions ν_A ranges from 10^4 s^{-1} (200 Torr) to $2 \times 10^6 \text{ s}^{-1}$ (1 Torr).

To express ν_R , both the three-body collisional radiative recombination of Ar^+ (frequency ν_R^{CR}) and the dissociative recombination of Ar_2^+ (frequency ν_R^{D}) have to be taken into account.

$$\nu_R = \nu_R^{\text{CR}} + \nu_R^{\text{D}} \quad (16)$$

$$\nu_R^{\text{CR}} = \alpha_{\text{CR}} [\text{Ar}^+] \quad (17)$$

$$\nu_R^{\text{D}} = \alpha_{\text{D}} [\text{Ar}_2^+] \quad (18)$$

α denotes the recombination coefficient and is expressed in $\text{cm}^3 \text{ s}^{-1}$. α_{CR} depends on electron density and electron temperature and has been calculated from Chen's values [10]. Under our conditions α_{CR} ranges from $10^{-12} \text{ cm}^3 \text{ s}^{-1}$ to $10^{-11} \text{ cm}^3 \text{ s}^{-1}$. On the other hand α_{D} only depends on electron and neutral temperatures. α_{D} has been calculated from T.F O'Malley *et al.* values [11] and is about $10^{-8} \text{ cm}^3 \text{ s}^{-1}$.

Nevertheless the main recombination loss process can only be determined if Ar_2^+ and Ar^+ densities are known. First of all, $[\text{Ar}^+]$ and $[\text{Ar}_2^+]$ are related to n_e by the neutrality condition,

$$[\text{Ar}^+] + [\text{Ar}_2^+] = n_e. \quad (19)$$

Secondly $[\text{Ar}_2^+]$ is deduced from its steady state equation, assuming Ar_2^+ is created by three-body collisions ($\text{Ar}^+ + 2 \text{Ar} \rightarrow \text{Ar}_2^+ + \text{Ar}$) which rate constant is denoted K and equals $2.2 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ [12] and destroyed by dissociative recombination

$$\frac{\partial [\text{Ar}_2^+]}{\partial t} = K n_0^2 [\text{Ar}^+] - \alpha_{\text{D}} n_e [\text{Ar}_2^+] = 0. \quad (20)$$

Equations (19) and (20) yield Ar^+ and Ar_2^+ densities as functions of neutral and electron densities and temperatures. Thus they yield the recombination loss frequencies ν_R^{CR} and ν_R^{D} [(17) and (18)].

4.3.2 Variation of $\nu_{\text{loss}}^{\text{eff}}$ with the pressure and the electron density. — The effective loss frequency is the sum of three terms

$$\nu_{\text{loss}}^{\text{eff}} = \nu_A + \nu_R^{\text{CR}} + \nu_R^{\text{D}}.$$

We have plotted the variations of ν_A , ν_R^{CR} , ν_R^{D} , versus the pressure for various electron densities ($n_e = 5 \times 10^{12}, 5 \times 10^{13}, 5 \times 10^{14} \text{ cm}^{-3}$) in figure 7.

First of all we note that, whatever the pressure and the electron density, ν_R^{CR} is negligible with regards to ν_R^{D} . We conclude that the dominant recombination process is dissociative recombination of Ar_2^+ , which means that Ar_2^+ plays a dominant role in the discharge.

Fig. 7. — Various loss frequencies versus the pressure assuming $T_e = 10^4 \text{ K}$, $T_0 = 1500 \text{ K}$, $a = 1 \text{ mm}$. Various loss processes: (A) ambipolar diffusion, (B) dissociative recombination (C) collisional-radiative. Values of n_e : (—) $5 \times 10^{12} \text{ cm}^{-3}$, (---) $5 \times 10^{13} \text{ cm}^{-3}$, (....) $5 \times 10^{14} \text{ cm}^{-3}$.

Secondly, figure 7 illustrates the dominant electron loss processes as a function of pressure. The discharge is governed by ambipolar diffusion up to about 10 Torr while dissociative recombination dominates above 100 Torr. Since ν_A decreases as p increases and ν_R increases with p , the effective loss frequency exhibits a minimum when ambipolar diffusion and dissociative recombination are comparable.

Lastly, we consider the variations of $\nu_R = \nu_R^{\text{D}}$ with electron density. Both the Ar_2^+ density $[\text{Ar}_2^+]$ and

Fig. 8. — Dependence on the electron density of the estimated dissociative recombination loss frequency (—) and Ar_2^+ density (...), assuming $a=1$ mm, $T_e = 10^4$ K, $T_0 = 1500$ K, $p=100$ Torr (i.e., $n_0 = 6.5 \times 10^{17} \text{ cm}^{-3}$).

ν_R are plotted in figure 8. From relations (18) and (20) they can be written in the simplified form :

$$[\text{Ar}_2^+] = n_e \left/ \left(1 + \frac{\alpha_D}{K \cdot n_0^2} n_e \right) \right. \quad (22)$$

$$\nu_R = K n_0^2 \left/ \left(1 + \frac{K \cdot n_0^2}{\alpha_D \cdot n_e} \right) \right. \quad (23)$$

Thus two physical limits appear :

— at low electron densities ($n_e \ll 10^{13} \text{ cm}^{-3}$) $[\text{Ar}_2^+]$ is nearly equal to n_e and ν_R is proportional to n_e .

— at high electron densities ($n_e \gg 10^{13} \text{ cm}^{-3}$) ν_R and $[\text{Ar}_2^+]$ are independent of n_e . Moreover $[\text{Ar}_2^+]$ is proportional to n_0^2 .

Under our experimental conditions ($10 \text{ Torr} \leq p \leq 200 \text{ Torr}$), the electron density ranges from about 10^{13} cm^{-3} at the end of the discharge to a few 10^{14} cm^{-3} at the excitation gap (cf. Fig. 4). Hence ν_R and $[\text{Ar}_2^+]$ have only a weak dependence on n_e , and thus are almost constant along the discharge (except at the end of the plasma column), in spite of the electron density gradient. Such calculations lead to about 10^{12} cm^{-3} Ar_2^+ densities, which confirms the dominant role of Ar_2^+ in the discharge.

5. Discussion and conclusion.

5.1 DISCUSSION. — As it was previously pointed out, $\theta_{\text{ion}} (= eV^+ \nu_{\text{loss}}^{\text{eff}})$ is almost independent of the electron density under our experimental conditions. Thus we can unambiguously plot the estimated values of θ_{el} , θ_{ion} and the experimental values of θ versus the pressure (cf. Fig. 9).

Fig. 9. — Estimated and experimental values of θ versus the pressure in several tubes assuming $T_e = 10^4$ K. Experimental values of θ : (O), $a=1$ mm ; (Δ), $a=1.75$ mm ; estimated θ_{el} : (●), $a=1$ mm ; ($\blacktriangle$), $a=1.75$ mm ; estimated θ_{ion} : (—), $a=1$ mm ; (---), $a=1.75$ mm.

θ_{ion} is plotted assuming T_0 increases linearly with p from 1 000 K at 10 Torr to 2 000 K at 200 Torr. Anyway T_0 has not been measured and has been estimated from low pressure results and from higher pressure spectroscopic measurements [15]. The same neutral temperature has been used whatever the tube diameter ; nevertheless we can expect T_0 to be lower in the largest tube, so that the dashed curve ought to be underestimated for medium pressures.

Firstly we note that θ_{el} is small with regards to θ , whatever the pressure.

Next we check that θ_{ion} is smaller than θ and moreover is about half of θ .

We have previously pointed out that θ_{ion} is independent of the electron density, which is to link to the experimental result of independence of θ on n_e (i.e., on Z). Thus this independence is due to the Ar_2^+ kinetic in the discharge.

Moreover θ_{ion} and θ have similar variations with the pressure. Particularly θ_{ion} and θ exhibit their minimum at the same pressure, i.e. about 20 Torr in the 3.5 mm diameter tube and about 50 Torr in the 2 mm tube.

Thus the estimated θ_{ion} describes the behaviour of θ with both the electron density and the pressure quite well.

5.2 CONCLUSION. — Argon surface wave discharges have been characterized at medium pressure in

capillary tubes. It has been experimentally pointed out that the mean power needed to maintain an electron in the discharge, θ , is independent of the electron density and exhibits a minimum with the pressure.

A simple model of the energy balance, estimating the electron loss frequency, leads to approximate values of θ . It points out that the main electron loss process is ambipolar diffusion up to 10 Torr and dissociative recombination of Ar_2^+ above 100 Torr.

Furthermore the estimated values of θ have almost the same behaviour as the experimental values with both the electron density and the pressure.

The smaller the tube, the higher is the pressure of the minimum of θ . This particular pressure is of some interest since the power needed to maintain a given number of electron is then minimized. In particular, discharges for chemical analysis by spectroscopical emission could operate at such pressures, high enough to excite the sample.

References

- [1] MOISAN, BEAUDRY, C., LEPRINCE, P., *Plasma Sci. PS3* (1975) 55.
 - [2] MAREC, J., BLOYET, E., CHAKER, M., LEPRINCE, P. and NGHIEM, P., *Elec. Breakdown and Discharges in Gases* (Plenum Pub. Corp.) B, 1983, p. 347.
 - [3] CHAKER, M., NGHIEM, P., BLOYET, E., LEPRINCE, P. and MAREC, J., *J. Physique Lett.* **43** (1982) 71.
 - [4] BOISSE-LAPORTE, C., GRANIER, A., DERVISEVIC, E., LEPRINCE, P. and MAREC, J., *J. Phys. D* **20** (1987) 197.
 - [5] FERREIRA, C., *J. Phys. D* **14** (1981) 1811.
 - [6] FERREIRA, C., *J. Phys. D* **16** (1983) 1673.
 - [7] BOISSE-LAPORTE, C., GRANIER, A., BLOYET, E., LEPRINCE, P. and MAREC, J., *J. Appl. Phys.* **61** (1987) 1740.
 - [8] GRANIER, A., BOISSE-LAPORTE, C., LEPRINCE, P., MAREC, J. and NGHIEM, P., *J. Phys. D* **20** (1987) 204.
 - [9] NGHIEM, P., CHAKER, M., BLOYET, E., LEPRINCE, P. and MAREC, J., *J. Appl. Phys.* **53** (1982) 2920.
 - [10] CHEN, C. J., *J. Chem. Phys.* **50** (1969) 1560.
 - [11] O'MALLEY, T. F., CUNNINGHAM, A. J. and HOBSON, R. M., *J. Phys. B* **5** (1972) 2126.
 - [12] FITZWILSON, R. L. and CHANIN, L. M., *J. Appl. Phys.* **44** (1973) 5337.
 - [13] ZANDER, A. T. and HIEFTJE, G. M., *Appl. Spectrosc.* **35** (1981) 357.
 - [14] GOODE, S. R. and BAUGHMAN, K. W., *Appl. Spectrosc.* **38** (1984) 755.
 - [15] MOUSSOUNDA, P. S., RANSON, P. and MERMET, J. MM., *Spectrochim. Acta* **40 B** (1985) 641.
-