

Caesium volume effects on multicusp ion source kinetics

D. Pagano¹, C.Gorse^{1,2}, M. Capitelli^{1,2}

¹ Department of Chemistry, University of Bari, 70126 Bari, Italy

² Istituto di Metodologie Inorganiche e Plasmi, Sezione Territoriale di Bari, 70126 Bari, Italy

In multicusp sources different discharge conditions (discharge current, pressure, etc.) modify the negative ion yield. An alternative way of influencing the whole kinetics, and therefore the negative ion production, is to fill up the device chamber with a gas mixture

In this work we investigate how the presence of caesium can affect the hydrogen kinetics in a magnetic multipole ion source through a zero-dimensional kinetic model. In particular we focus our attention just on volume processes (elastic collisions, electronic excitation and ionization) showing their effect on the electron kinetics and then on the negative ion production.

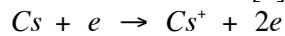
1. Introduction

An effective production of negative hydrogen ions represents one of the most important topic in the thermonuclear research field due to their efficient conversion in high energy neutral beams used for fusion plasma injection [1]. Different kinds of plasma sources are studied both experimentally and theoretically in order to optimize negative ion production [2]. In particular two major types of negative ion sources are investigated: surface sources and volume sources. We focused our attention on the volume production of negative ions [3] in multicusp sources where the plasma is generated by electrons thermoemitted by one or more hot filaments and accelerated by the voltage between the filaments and the source walls.

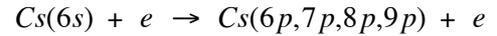
The behaviour of these devices, with respect to their efficiency in negative ion production, can be controlled acting on different parameters, like pressure or current discharge, which influence the chemical kinetics.

The optimization of both the source geometry and the discharge conditions is not the only way to affect the negative ion production, as shown by experiments [4] conducted by mixing various gases to hydrogen. Addition of another chemical species modifies the hydrogen chemical kinetics through several mechanisms. Here we will consider the effect of caesium on hydrogen kinetics, focusing our attention just on those processes which involve electrons and caesium atoms, neglecting the reactions with hydrogen molecules or atoms and on the surfaces.

Due to its low ionization potential (3.89 eV), caesium should affect the ionization degree of the plasma through the direct reaction [5]



The cross section for this ionization process is a factor of 10 higher than the corresponding ones for H₂ and H, and presents a lower threshold energy. A similar situation holds for the electron impact excitation cross sections [6]



Moreover the electron momentum transfer cross section [7] in caesium presents two maxima, each one 100 times as high as the corresponding maxima in H₂ and H values: small concentrations of Cs in gas phase could therefore affect the EEDF of Cs–H₂ mixtures as well as the ionization degree of the plasma.

As for hydrogen [8], an accurate description of caesium ionization should require the knowledge of differential cross sections in order to account for the energy sharing between the incident electron emerging from the ionizing collision and the secondary electron produced. These data are not available for caesium then we have treat this ionization as a simple inelastic process with the secondary electron produced at zero energy (in the lowest energy interval).

These processes induced by caesium, act indirectly on the negative ion production through their effect on the electron kinetics, but other processes (not included here) can affect directly the heavy particle kinetics.

We develop a zero-dimensional kinetic model to describe, through a state-to-state approach, the complex behaviour of atoms, molecules, ions and electrons taking part in a large number of processes involving vibrationally and electronically excited species [9].

2. Kinetic model

The crucial point in the kinetic description of such devices is constituted by the necessity to follow the simultaneous time evolution of heavy particle and electron systems. The first one is represented by a set of master equations including gains and the losses for each species due to any specific reaction [9], while the second one is described by the Boltzmann equation [10][11].

$$\frac{\partial n(\varepsilon, t)}{\partial t} = - \left(\frac{\partial J_{el}}{\partial \varepsilon} \right)_{e-M} - \left(\frac{\partial J_{el}}{\partial \varepsilon} \right)_{e-e} + In + Ion + Sup + S - L \quad (1)$$

that provides the temporal evolution of the density of the electrons with energy in a certain interval. The terms on the right hand side are associated with all the collisional processes occurring in the plasma: the first two terms accounts for the flux of electrons along the energy axis due to elastic and Coulomb collisions respectively and the other terms corresponds to inelastic (*In*), ionizing (*Ion*), superelastic (*Sup*) collisions and electron losses in recombination and on the wall (*L*); finally *S* characterizes the system and represents the source term describing the injection of electrons in the source volume.

Our model starts reinterpreting the Boltzmann equation in the light of a state-to-state approach obtaining an overall description of the plasma kinetics represented by a unique master equations system including the time variation of heavy particles and representative electrons, i.e., the discretized electron energy intervals are treated like the vibrational or electronic levels of the molecule or of the atom. In this scheme, the rate coefficient for processes promoted by electrons does not take into account the overall energy distribution function,

$$k_i^e = \int_{\varepsilon_{thr}}^{\infty} \sigma_i(\varepsilon)v(\varepsilon)n(\varepsilon)d\varepsilon \quad (2)$$

but is only related to one specific energy interval and represents the rate coefficient of an excitation process promoted by an electron with a specific velocity.

$$k_i^e = \sigma_i(\varepsilon)v(\varepsilon) \quad (3)$$

This approach can be used also to describe elastic and Coulomb electron-electron collisions and allows to include the processes for caesium in a quite simple way simply adding the corresponding rate equations in the master equations system. The overall system evolves in time with a time step determined step by step through an adaptation technique based on the order of the numerical method adopted [12].

For what concerns the heavy particle kinetics two temperatures are set as parameters for molecules and atoms: $T_{H_2}=T_{H_2^+}=T_{H_3^+}$ and $T_H=T_{H^+}$; this separation implies that when a collision between an atom and a molecule occurs, like in V-Ta processes, another temperature, called “reduced”, must be defined as:

$$T^* = \frac{m_H T_{H_2} + m_{H_2} T_H}{m_H + m_{H_2}} \quad (4)$$

and the rate coefficient connected to this process will be calculated integrating the cross sections over a Maxwell distribution at this temperature.

The electron temperature is calculated self-consistently at each time step from the mean energy of the distribution for electrons considering just its low-energy part (electrons with energy up

to 10 eV). This represents an approximation, indeed, electron temperature could be only used to describe maxwellian EEDF: such a behaviour is not respected during the early times in the discharge when beam electrons, are dominant. These electrons cannot be responsible for the determination of the average properties of the plasma, thus a particular treatment should be applied.

3. Results and discussion

Present results have been calculated in the following conditions: P=4.5 mtorr, $I_d=0.1$ A $V_d=100$ V, assuming $T_H=4000$ K, $T_{H_2}=500$ K; the caesium temperature is set equal to T_{H_2} ; the geometrical and plasma parameters of the source are those reported in table 1. Caesium density is kept constant during the time evolution of the discharge; results for different caesium densities are compared with results obtained in a pure hydrogen discharge.

Table 1. Geometrical and plasma parameters of the source.

Source volume	3724 cm ³
Source surface	1456 cm ²
Plasma volume	1936 cm ³
Plasma surface	946 cm ²
Electron loss surface	41 cm ²
$T_H=T_{H^+}$	4000 K (0.35 eV)
$T_{H_2}=T_{H_2^+}=T_{H_3^+}$	500 K (0.04 eV)
γ_H	0.05

The presence of caesium acts directly on the electron kinetics modifying the behaviour of the EEDF and then the rate coefficients of all electronic processes. First we just insert in the kinetic scheme elastic collisions and electronic excitation, neglecting caesium ionization. Fig.1 compares the stationary EEDF obtained for a pure hydrogen discharge, with those calculated including just the effect of elastic and electronic excitation of caesium and those for an hydrogen caesiated discharge including first ionization. We can see that the main effect of caesium is to increase the number of electrons with energy larger than 1.5 eV as a consequence of the decreased importance of vibrational inelastic losses of electron-molecule collisions. The differences in any case become slight when elastic, inelastic and ionization collisions between electrons and caesium are included in the Boltzmann equation. As a global effect caesium in gas phase does not significantly alter the stationary values of electron density (fig. 2), electron temperature (fig. 3) and of negative ion density (fig. 4).

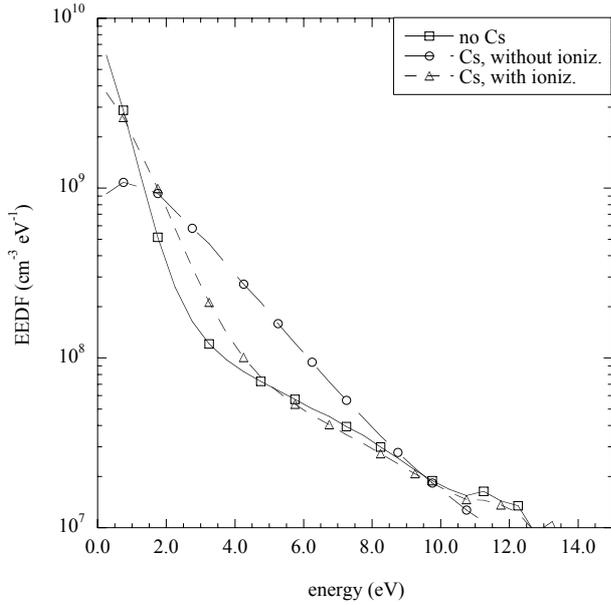


Fig.1. Effect of caesium on EEDF for $I_d=0.1$ A, $V_d=100$ V, $P_{H_2}=4.5$ mtorr, $P_{Cs}=10\%P_{H_2}$.

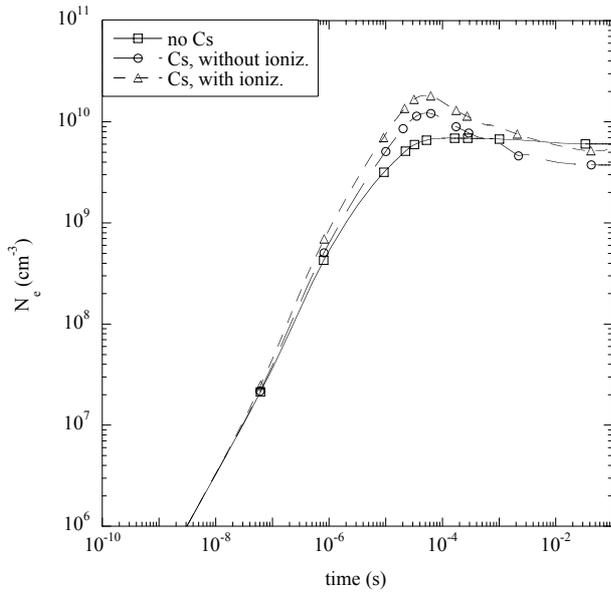


Fig.2. Effect of caesium on the total electron density for $I_d=0.1$ A, $V_d=100$ V, $P_{H_2}=4.5$ mtorr, $P_{Cs}=10\%P_{H_2}$.

A larger effect is indeed observed during the time evolution of the different quantities (see figs. 2-3) as a result of the time dependent interplay of the electron-caesium and electron-molecule energy exchange processes. This point can be important for pulsed discharges. These processes act decreasing the low energy electrons density with a corresponding increase in the electron temperature (fig. 3).

A decrease in the negative ion density is registered increasing the caesium density (fig. 4). The effect is more pronounced when caesium concentration is increased.

It is clear that other processes in the volume of the plasma, but also at the surface, play a key role in increasing the negative ion yield when a mixed discharge is considered.

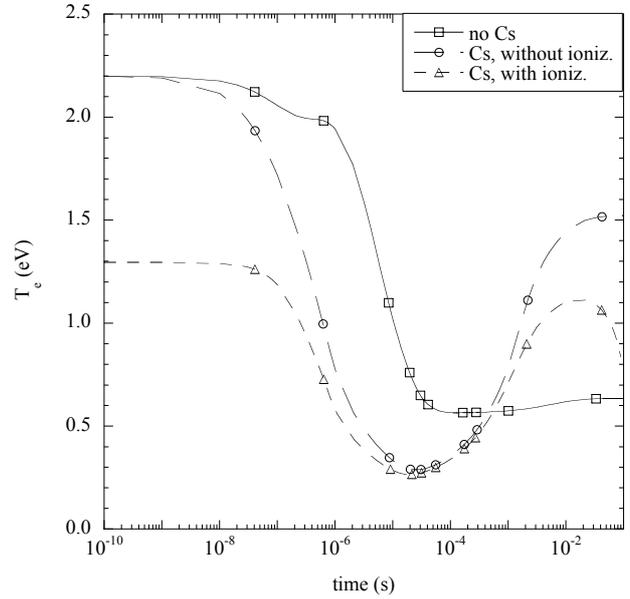


Fig. 3. Effect of caesium on the electron temperature for $I_d=0.1$ A, $V_d=100$ V, $P_{H_2}=4.5$ mtorr, $P_{Cs}=10\%P_{H_2}$.

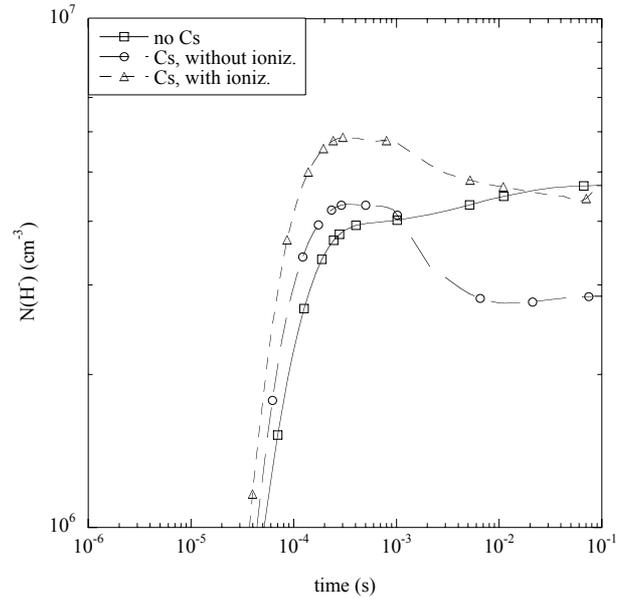


Fig. 4. Effect of caesium on the negative ion density for $I_d=0.1$ A, $V_d=100$ V, $P_{H_2}=4.5$ mtorr, $P_{Cs}=10\%P_{H_2}$.

4. Conclusions

In this work we have shown how the presence of caesium in the gas phase can affect the electron kinetics and, as a consequence, the heavy particle kinetics with a particular focus on negative ion yield, just taking into account processes between caesium atoms and electrons.

The numerical scheme adopted allows to add processes for caesium species in a very simple way.

Presented results show how different caesium processes affect the electron kinetics suggesting that other mechanisms should play a role in enhancing negative ion production. This will be the object of future studies that will take into account also processes involving heavy particles (hydrogen molecules and atoms). Moreover caesium seems to be very important in enhancing the production of negative ions through surface processes, lowering the work function of the wall material.

5. Acknowledgment

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6. References

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