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Segmented plasmatron for simulation of re-entry conditions in a planetary atmosphere

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The experimental studies are carried out to adapt the plasmatron functioning to simulate re-entry conditions in a planetary atmosphere. The plasma flow is produced using argon or nitrogen arc and nitrogen or carbon dioxide is introduced into plasma jet. Although the gas introduced into plasma jet is injected behind the arc it influences the arc characteristics and dynamics of flow. This effect is studied in detail. Emission spectra of atomic nitrogen and ionized molecular nitrogen (N_2^+) are also recorded and analyzed. The atomic emission is studied in the infra-red region and has allowed the determination of an excitation temperature. The electron density is determined from the continuum radiation, and the rotational and vibrational temperatures are determined from the 1st negative system of N_2^+.

1. Introduction

During the hypersonic flight of a spacecraft in the upper layers of an atmosphere of a planet such as Mars, Venus, Earth, the shock wave in front of the vehicle induces a large energy flux toward to the surface. This flux of energy results from transformation of kinetic energy into thermal energy leading to dissociation and ionization of particles and radiative effects. For very high speed of the spacecraft, the radiative energy is predominant compared to convective energy. The knowledge of this radiative flux is therefore essential to define and optimize the thermal protection system (TPS) of spacecraft for planetary exploration. This knowledge is based on studies involving both modelling and measurements carried out in ground test facilities rebuilding the flow properties of plasmas (non-equilibrium ionization process and radiative effects). The results of these experiments are subsequently used to validate plasma models. One of tests facilities used to simulate this kind of plasma effects is D.C. segmented plasmatron. The experimental studies are carried out to adapt the plasmatron, electric power supply and diagnostic set-up to simulate re-entry conditions in a planetary atmosphere. Especially the principle characteristics of plasmatron working with different gases such as argon, carbon dioxide, nitrogen and the mixture of these gases as well as stability of plasma jet are investigated. The initial study presented in this paper was focused on a pure nitrogen plasma flow. Emission spectra of atomic nitrogen and ionized molecular nitrogen (N_2^+) were recorded using emission spectroscopy and analyzed. The atomic emission was studied in the infra-red region and has allowed the determination of an excitation temperature. The electron density was determined from the continuum radiation, and the rotational and vibrational temperatures from the 1st negative system of N_2^+.

2. Segmented plasmatron

The plasmatron consists of a thoriated tungsten rod cathode and copper cylinder sections, insulated by means of rings used to gas injection in such a way that a vortex develops stabilizing flow. Through the ring behind the section serving as anode the next gas is injected in direction opposite to the first vortex. Gas flow rates vary between 0.6 and 1.6 g/s and static pressure between 1 and 100 kPa.

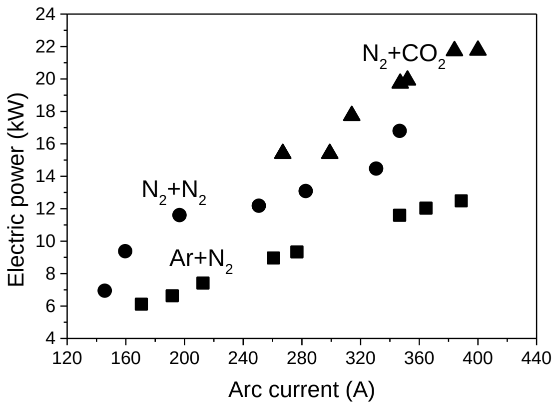


Fig.1. Input electric power for gas flow rate 0.8g/s injected into arc and 0.6g/s into plasma jet at pressure 6kPa; ■ - argon arc and nitrogen introduce into plasma jet; nitrogen arc and ● – nitrogen or ▲ – carbon dioxide introduce into plasma jet

The arc is sustained between the cathode and the first section serving as an anode. The plasmatron is working with arc current from 50 to 440 A and the arc voltage depends on distance between cathode and anode, gas flow rate, pressure and arc current. Input electric power (Fig.1) is a quasi-linear function of current and corresponds approximately to 35 W/A for argon arc and nitrogen introduced into plasma jet, 45 W/A for nitrogen arc and nitrogen introduced into plasma jet and 55 W/A when carbon dioxide is introduced.

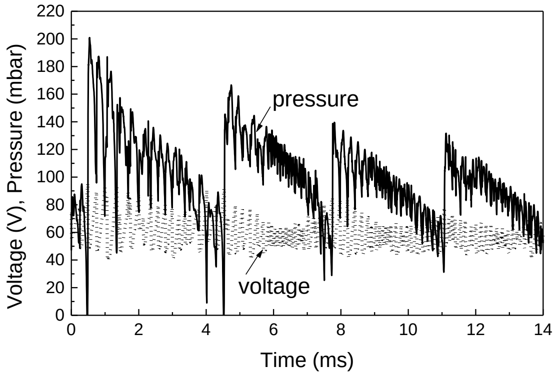
Gas heated in the arc, forms plasma jet flowing into a low pressure chamber. The flow delivered by this source is axisymmetric along the plasmatron axis and stationary. At the inlet to the low pressure chamber, the flow can be subsonic or supersonic with a Mach number around 1.

3. Dynamics of arc and plasma jet

The plasma flow produced by plasmatron results from very complex and coupled physical, electrical and flow phenomena. The fluctuation of arc current and voltage therefore the power input can influence temperature and ionization-recombination processes. The pressure fluctuation influences particles densities. Such a condition must be taken into account interpreting optical emission spectroscopy results. In Fig.2 the large pressure fluctuations are presented which do not correspond to the voltage fluctuations. These fluctuations results from vortices movements downstream of flow. The velocity of this movement depends on flow acceleration. When the currents increase the temperature and velocity increases too and the vortices move faster. For high current, in case of considered plasmatron construction, higher than 400 A the vortices are considerably braked as we can expect due to viscosity effect.

The vortices movement depends also on gas nature. For argon arc the velocity is two times faster than in nitrogen arc. The Fig. 2 shows the important amplitude of fluctuation about 150 mb. Fortunately this amplitude decreases with arc current and for current higher than 300 A do not exceed 50mbar. For carbon dioxide injected into nitrogen jet the amplitudes of pressure fluctuation are more important but do not exceed 60 mbar.

Other phenomenon, that causes important fluctuation is anodic spot movement [1-3]. It influences on plasma torch working time, flow and electric parameters, plasma composition, spectra lines. The different modes of this anodic spot behavior are identified. In our operating plasmatron conditions for argon arc we observe that the anodic spot moves upstream, the arc extends and the arc voltage increases, then the spot draws back, the arc shortens and the voltage decrease. During the arc spot movement the breakdowns in the gas layer between arc core and the wall occur.



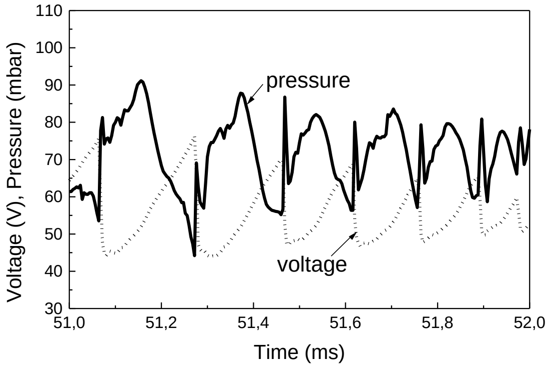


Fig.2. Arc voltage and pressure recorded during 14 and 1 ms at arc current 245 A and nitrogen flow rate 0.8 g/s introduced into arc and 0.6 g/s into plasma jet

In certain conditions the arc spot moves upstream then the breakdown occurs, the new spot is created and moves upstream again. In this case the arc spot does not move downstream. Detached hot part of arc moves in flow direction increasing the pressure, then the temperature and pressure inside this part decrease the more, that the reactions occurs and molecular gas is created. This behaviour is illustrated by voltage and pressure recorded during 1 ms in Fig.2.

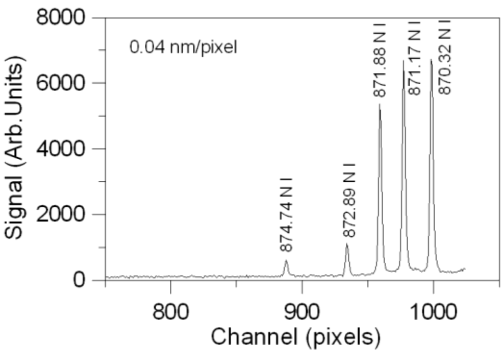
Depending on gas nature and mass flow rate two different types of breakdown are observed - thermal breakdown or electrical one [4]. When the electric field in gas layer between arc core and the wall grows enough, the electric breakdown appears, provoking the fast diminution of the arc length thus the arc voltage (Fig. 2).

The thermal breakdown is characterised by the growth time much longer than in case of electric one because this breakdown is caused by heating of the gas layer between hot arc core and cold wall. In this situation the amplitude of fluctuations are smaller than in case of electric breakdown. In our conditions we observe thermal breakdown in argon arc and carbon dioxide introduced into plasma jet. In nitrogen arc we never observe thermal breakdowns. We must note that arc shortening caused by electric breakdown is accompanied by erosion of the cooper from anode. Then, the spectrum is rich in copper lines and these lines are superimposed on the molecular lines making analysis impossible. In general we observe a correlation between the dynamics of the arc and spectra lines but it is not easy to determine.

4. Optical emission spectroscopy

The emission spectra of nitrogen plasma consisted of lines of atomic nitrogen and N_2^+ molecular bands. The lines of nitrogen were clearly distinguishable only in the infrared region. Some characteristic spectra of the atomic lines of nitrogen are shown in Fig.3. Using intensities of spectral lines relative and absolute population densities are determined.

The excitation temperature T_{exc} was determined from the relative intensities of the following N I lines: 870.32, 871.17, 871.88, 872.89, 874.74, 902.89, 904.58, 904.99, 906.04 nm (see Fig.3). The upper levels of these lines have energies 11.75 eV, 12.97 eV and 13.72 eV. All these lines were checked to be not influenced by self-absorption. The energy gap between the levels is wide enough to determine T_{exc} with good accuracy and all these lines could be registered together with the grating 600 g/mm. Unfortunately the lines originating from the transitions from highly excited levels (902.89 – 906.04 nm) are very weak which results in poor accuracy of Abel inversion. As a result the radial distribution of the electron temperature is flat with T_{exc} about 8000 K.



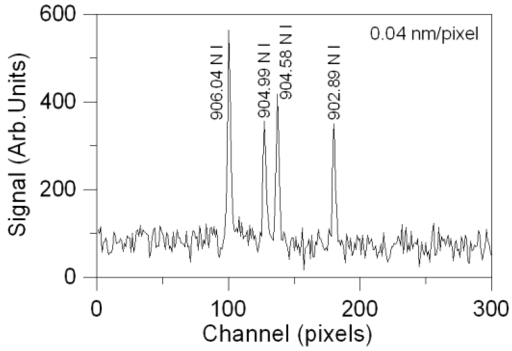


Fig. 3. Spectral lines of atomic nitrogen in infrared region

The absolute calibration allows the determination of population densities of the upper levels of measured lines. It seems that all levels with energy 11.75 eV or higher are in equilibrium with a T_{exc} of about 8000 K. The population density of upper level of 746.83 nm N I line as a function of a distance from the anode is shown in Fig.4.

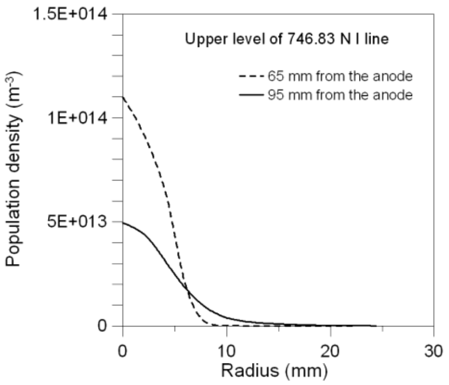


Fig.4. Population density of upper level of 746.83 nm N I line

The Stark broadening of spectral lines was too small and hence the electron density was determined from the continuum radiation. The total continuum emission coefficient can be written as

$$\varepsilon_{total} = \varepsilon_{ei}^{ff}(\lambda) + \varepsilon^{fb}(\lambda) + \varepsilon_{ea}^{ff}(\lambda)$$

where indices *fb* and *ff* denote free-bound and free-free transitions i.e., the emission due to the recombination and the Bremsstrahlung, respectively and *ei* and *ea* denote electron-ion and electron-atom collisions. It has been found that in our conditions the emission due to recombination is dominant, the two other processes did not exceed 6% of the total radiation. The $\varepsilon^{fb}(\lambda)$ was calculated with the use of photoionization cross sections taken from [5].

The radial distributions of the electron density calculated from the continuum radiation at ~ 430 nm are shown in Fig.5.

The observed molecular spectra consisted mainly from the 1st negative system of N_2^+. The rotational and vibrational temperatures were determined by comparing synthetic spectra with spectroscopic measurements. Both spectra are shown in Fig.6. The best fit is obtained for rotational temperature T_R = 6500 K and vibrational temperature T_V = 10000 K indicating a non-equilibrium plasma flow.

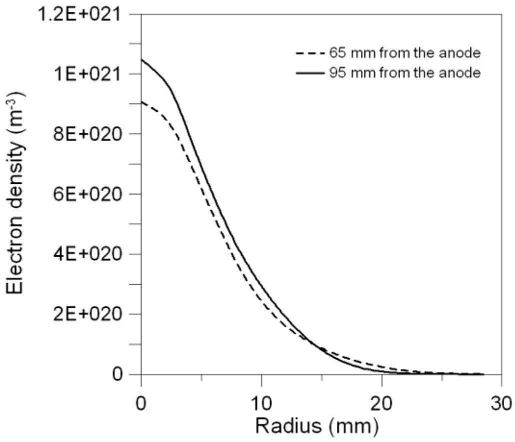


Fig. 5. Radial distributions of the electron density at two different distances from the anode

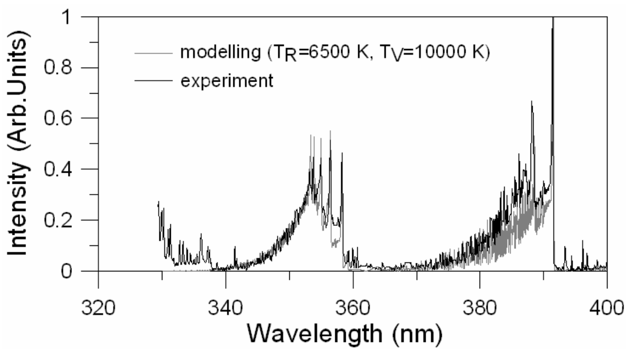


Fig. 6. Experimental and synthetic spectra of molecular bands at a distance 95 mm from the anode

The results show that the plasma produced by the segmented plasmatron is in non-equilibrium condition. This is what can be expected. The criterion for local thermodynamic equilibrium (LTE) has the form [6]:

$$N_e \geq N_e^{cr} = 1.6 \times 10^{18} T_e^{1/2} (\Delta E)^3$$

where N_e^{cr} is the critical electron density (in m^{-3}) necessary to fulfil LTE conditions and ΔE is the largest energy gap of atomic (ionic) energy level system (in eV). Since such energy gap for N I is 10.33 eV (the level with energy 3.55 eV has been neglected in these considerations because the transition rate to this level is weak) the electron density necessary to fulfil the above criterion is ~ 1.6×10^{23} m^{-3} at a temperature of 8000 K. Even taking into account that in practice this criterion can be lowered one order of magnitude because of the absorption of resonance lines the electron density necessary to fulfil LTE conditions is still 10 times higher than that observed in the experiment. In addition the transport of particles can also influence the Saha balance.

5. Conclusion

The results shows that the segmented plasmatron can be used to simulate some processes occurring during re-entry conditions in planetary atmosphere. Especially the radiation of plasma composed from excited and ionized spaces of different gases can be studied. However the fluctuation of plasma parameters resulting from gas flow and arc dynamics must be taken into account.

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