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Numerical Model for the Study of the Velocity Dependence Of the Ionisation Growth in Gas Discharge Plasma

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Abstract:

The influence of the velocity on the development of the ionisation has been investigated for the study-state plasma. The cascade ionisation (represented by a constant ionisation coefficient) was assumed to occur over a finite length of an infinite cylinder and the only loss processes considered over this length were electron diffusion. The calculation has been carried out for an open cylinder by using a two dimensional numerical model. The required cascade ionisation, to sustain a given plasma density, has been calculated as a function of velocity.
Keywords: optical discharge, Plasma, Ionisation

Introduction:

The theoretical studies, which discuss the plasma distribution throughout an open and closed tube as well as a positive column analytically and numerically based on the continuity equation, have been subject for many researchers: Romig (1959), Zel'dovich & Raizer (1964), Evans (1968), Montogfier (1972), Richard (1983), Nicholas and Sajjadi (1985), Morgan (1986), AL-Hashimi (1990, 1996, 1999), Shargi (1997), Al-Kelly (1996, 1999). Moreover the cascade ionisation has been investigated by a considerable amount of theoretical and experimental works: Zel'dovich and Raizer (1965), Ireland and Morgan (1972), Nielson and Rockwood (1972), Rambo (2001), Schwarz and Diels (2001), Al-Hashimi and Kelly (1996) and Al-Hashimi and Sharqi (2010). Some of these studies considered the presence of two major loss processes, these are the diffusion and recombination. The other studies considered the presence of one of them and neglect the other. The differences in the treatment depend on the assumption that the case subjected to. However, none of these studies appears to give a general analytical or numerical solution for this problem, which enables us to determine the plasma and its distribution throughout a finite length. The problem becomes more complicated when the gas velocity is taken into account. In common with all these studies, the present paper exhibits a development of a numerical model that combines the plasma density with gas flow through a cylindrical discharge tube, taking into account the diffusion coefficient as a major loss process.

Formation of the Problem:

In the gas discharge, ionisation is caused by the collision of the free electrons with the gas atoms. The actual energy distribution of these electrons will depend on the assumption that simulates the mechanisms by which they are generated. A numerical model has been introduced to describe the ionisation development in a gas discharge plasma with the flow. This model is constructed in terms of the continuity equations that must be ensured satisfactorily. The charge conservation of each particle would be activated in the discharge. The ionisation equation may then be solved subjected to appropriate boundary condition. To achieve this procedure it is essentiall to know which elementary ionisation processes can occur. By these, a selection of the dominated conditions being studied either on the basis of experimental measurements or from a preliminary magnitude order. As a conclusion, the following assumptions are assumed.

1) The thermal and chemical processes will not be considered.
2) Diffusion controls discharge will be considered, while the recombination is assumed to take place only at the boundaries.
3) Any inertial drift velocity that might occur would be incorporated into an effective diffusion coefficient.
4) The degree of ionisation N_e/N is small compared to unity so that the conservation equations for the neutral species may be uncoupled from those of the charged particles.
5) A quasi-neutral discharge would be assumed in which $N_e \approx N_i$ where N_e and N_i stand for electrons and ions densities respectively.
6) The effect of the meta-stable atoms and other losses on the plasma production would be neglected.
7) The mean energy of the particles in the volume comes from a given imposed electromagnetic field.
8) A sufficiently strong filed is applied. This is necessary for a rapidly ionized electron to be excited by the absorption of a few photons. However, if the field is not strong enough to provide a rapid ionisation of the exited atom, the lost energy by the electron to excitation hinders the development of the cascade.

The net rate of production of electrons in an electrical discharge, in which these loss mechanisms exist, may be expressed mathematically as a generalized continuity equation

$$\frac{\partial N_e}{\partial t} = D_a \nabla^2 N_e + \alpha N_e \omega_e - \rho N_e \omega_e - \nabla \cdot N_e \omega_e \qquad (1)$$

And the net rate of production of ions

$$\frac{\partial N_i}{\partial t} = \alpha N_e \omega_e + \nabla \cdot N_i \omega_i \qquad (2)$$

Where N_e, N_i are electrons and ions density, ω_e, ω_i are electrons and ions drift velocity, α is the ionisation coefficient, ρ is the recombination coefficient, D_a is the ambipolar diffusion coefficient. According to the above assumptions and by taking into account the fact that steady state discharge occurs. When the production of new charged particles in the volume equals these loss to the volume by any of the loss processes mentioned above equations(1) and (2) are written in the form:

$$D_a \nabla^2 N - U \cdot \nabla N + \alpha_c N = 0 \qquad (3)$$

Equation (3) represents the governing equation for the flowing quasi-neutral steady state ionization process. This includes the decay of the plasma by diffusion, to the wall and the loss due to the drift velocity, also counts the only gain term that is cascade ionisation.

The geometry simulates, to some extent, the flow in the plasma tunnel. It has been considered as a cylindrical tube that has an axial gas flow with an axial velocity V_z as shown in figure (1). The origin coordinates of the field applied concentric with the origin of the cylinder. The length of the effective area is 2L. The cascade ionisation over the length 2L is constant whereas zero everywhere (Romig 1959, AL-Hashmiy 1990, Shargi 1996). The general solution based on the integration over finite volume will be by of the form:

$$a_p \Omega_p = \sum_n a_{np} \Omega_{np} + b$$

Where the subscript (np) stands for neighbors point.

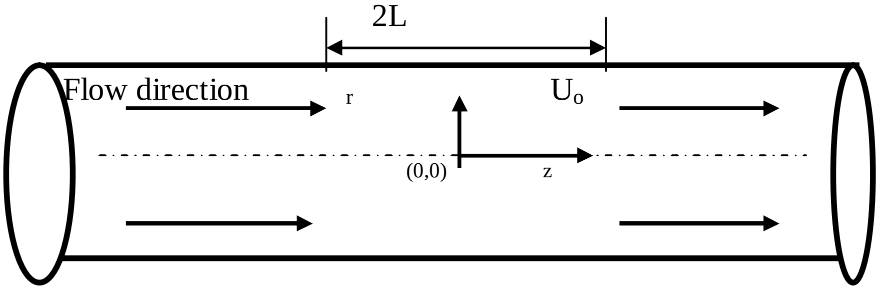

Fig. (1) The cylindrical discharge tube

Results and Discussion:

The steady state equation (3), needs to be solved. It has a convective term as well as a diffusion term in addition to a linear source term. Since the plasma flow equation is multidimensional and nonlinear, hence a finite difference technique provides the only means of the solution. The convective term U.∇N in equation (3) makes this equation one of the most difficult partial differential equation of continuum physics to be solved stably and accurately. The solution to this equation is based on dividing the working area to a mesh of 161*81 grid point. It has been assumed that the ionisation takes place in, almost, at the centre of this area. The first derivative in this equation is solved by upward technique and the second derivative is approached by central difference schemes. The gas flow through the cylindrical tube is assumed from left to right and the velocity profile is Laminar velocity, so that $U_z=U_o\,(1-R^2/R^2_o)$. Where R_o is the radius of the cylinder and R is the distance of the grid point from the axis of cylinder. It has been considered that the boundary of the plasma is isothermal. In this appreciable ionisation of the gas begins to occur at one side and vanish at the other side. The spatial plasma density distributions are calculated in the cylindrical discharge plasma. It has been found that the maximum plasma density is localized in the center of the discharge tube when the velocity of the gas is zero. But, when the gas velocity increases the position of the maximum plasma density moves a considerable distance toward the boundary of the discharge region. This is due to the difference between their energy balance conditions. The complete view of the plasma distribution and velocity behavior together with their productions are presented in figures (2-7). These figures also show that cascade begins at the boundary, i.e. the plasma density began to rise, on the axis as energy deposits from the strong field. The maximum plasma density reaches the center of the tube when the gas becomes stationary. The lines of constant plasma are presented in these figures by their projections. Also these figures show the radial distributions of plasma density experience fundamental changes in its value and uniformity. This is a direct result of the laminar flow velocity profile. It can be explained as the amount of ionization depends on the time that gas element spends in the laser or microwave field. This time is greater near the walls, where the velocity is slower, than on the axis. As a result it is expected that this form, of a complex profile exists through the discharge region. The relation between the ionization coefficient and the flow velocity at the discharge tube centre is presented in figure (8). This is for a constant value of ambipolar diffusion coefficient. It has been found that the value of cascade ionization increases as the flow velocity increases, i.e. the energy of the field must be increased to overcome the effect of flow velocity at the points of interest. Figure (9) shows the combined effect of the flow velocity on the plasma density, at the centre of the discharge for constant values of cascade ionization and diffusion coefficient. The plasma densities are full as a zero order Bessel function, and at velocity greater than 3.00 m/s the ionization is dying out. That means the gas will pass the region of strong filed without any absorption of energy.

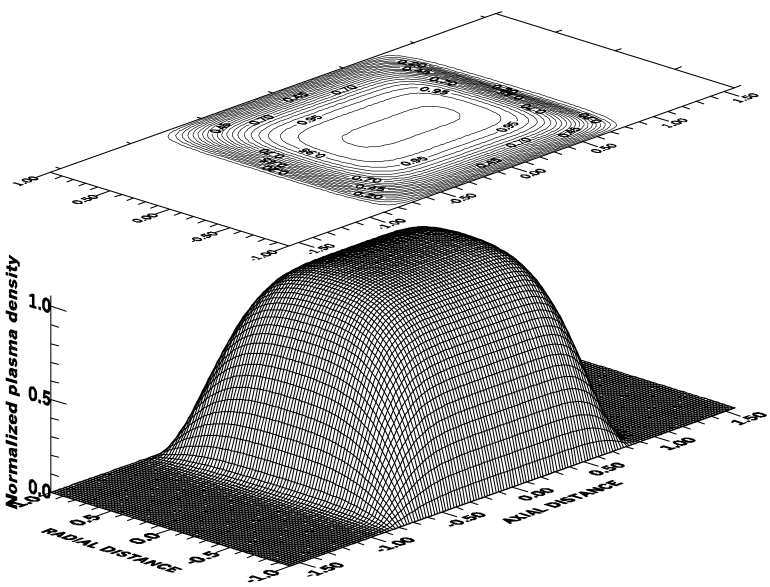

Fig. (2) Two-dimensional distribution of the plasma number density for a cylindrical discharge tube at zero velocity of gas.

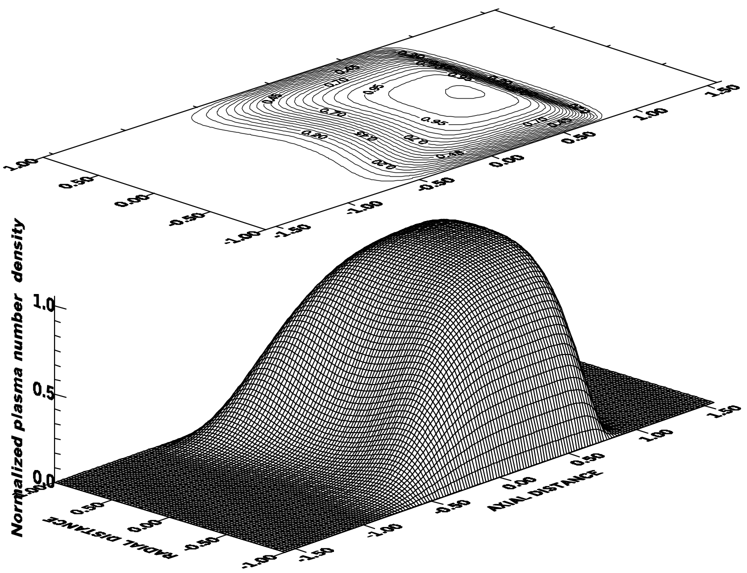

Fig. (3) Two-dimensional distribution of the plasma number density for A cylindrical discharge tube at gas flow velocity (Uo=1.00 m/s.)

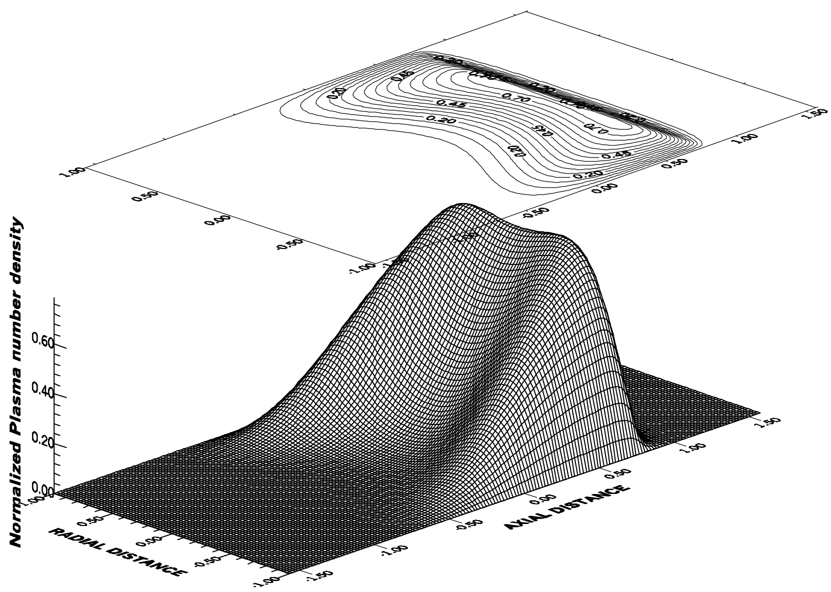

Fig. (4) Two-dimensional distribution of the plasma number density for A cylindrical Discharge tube at gas flow velocity (Uo=2.00 m/s.)

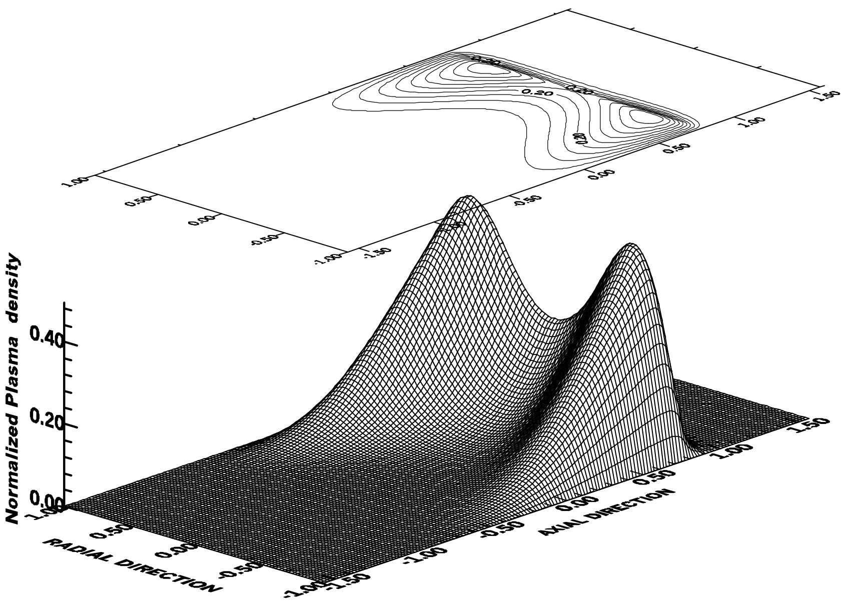

Fig. (5) Two-dimensional distribution of the plasma number density for A cylindrical Discharge tube at gas flow velocity (Uo=3.00 m/s.)

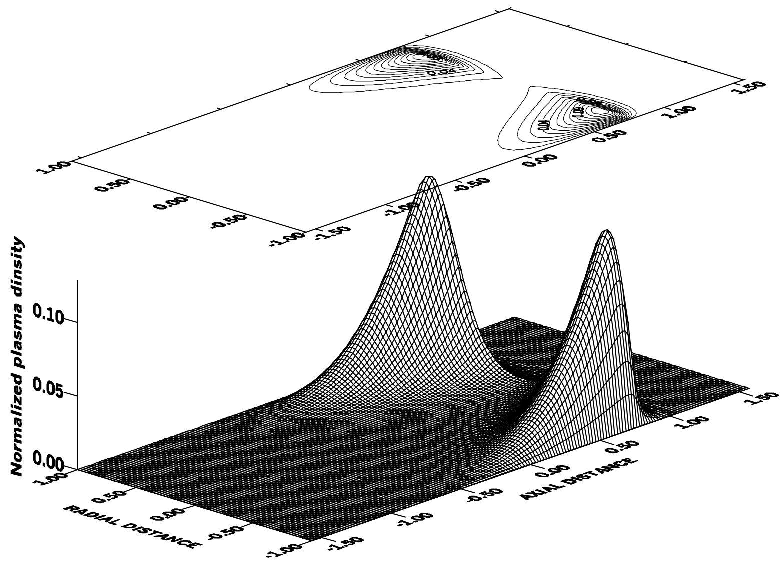

Fig. (6) Two-dimensional distribution of the plasma number density for A cylindrical discharge tube at gas flow velocity (Uo=5.00 m/s.)

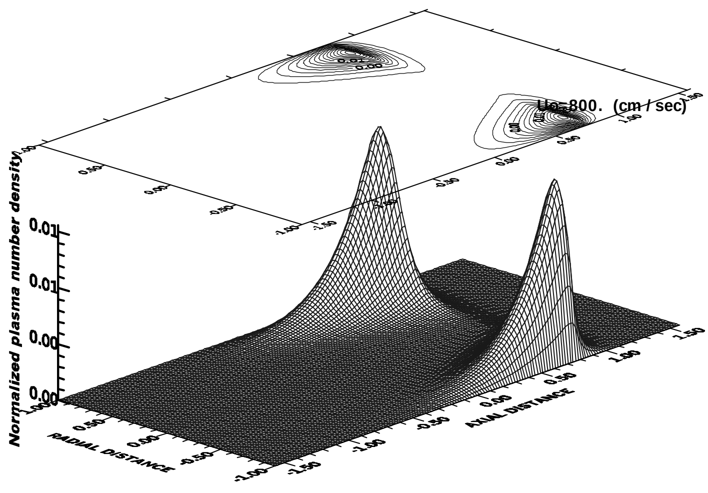

Fig. (7) Two-dimensional distribution of the plasma number density for A cylindrical Discharge tube at gas flow velocity (Uo=8.00 m/s.)

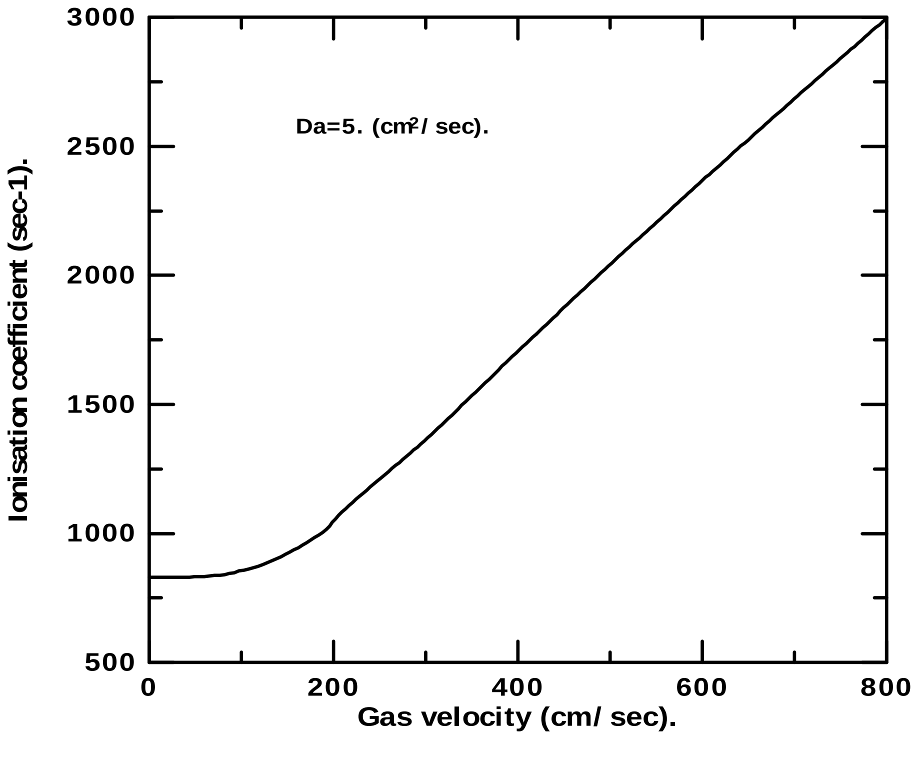

Fig. (8) Ionisation coefficient as a function of gas flow velocity for a cylindrical discharge tube for a constants Normalized plasma number density and diffusion coefficient .

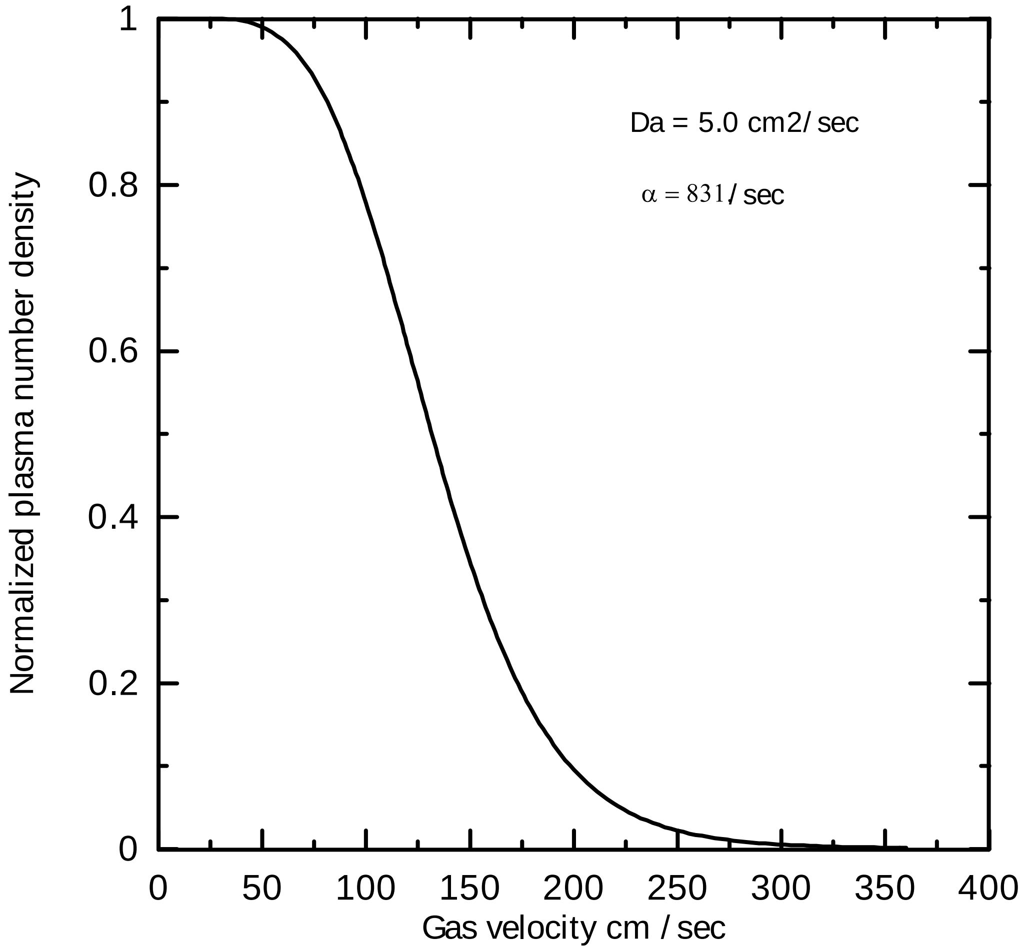

Fig. (9) Normalized plasma number density as a function of gas flow velocity at center cylindrical discharge tube (Z=0, R =0.) for a constants ionisation coefficient and diffusion coefficient

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