NUMERICAL MODELLING OF CORONA DISCHARGES AND THEIR INTERACTION WITH AERODYNAMICS

J.-C. Matéo-Vélez, F. Thivet, F. Rogier, G. Quinio
ONERA, France

P. Degond
MIP, France

Abstract

In the frame of the internal project PUMA (Plasma Used to Master Aerodynamic), ONERA is conducting fundamental studies in order to determine the limits within which air discharge plasmas are able to interact with aerodynamical phenomena. This paper focuses on the physical and numerical modeling of corona discharges and their interaction with aerodynamics. Using a simple plasma kinetic scheme, it is shown that the force exerted by a wire-to-wire corona discharge is sufficient to explain the effect on subsonic airflow. This force is of the same order as the one obtained thanks to dielectric barrier discharges (DBD).

1. Introduction

In the frame of the internal project PUMA (Plasmas Used to Master Aerodynamics), ONERA is conducting fundamental studies in order to determine the limits within which air discharge plasmas are able to interact with aerodynamical phenomena.

The investigations are focused on two typical configurations. The first one consists in using a discharge to modify the shock wave pattern in front of a supersonic spike body in order to control the flow unsteadiness. As recently reported [1], a truncated cone-cylinder model with a needle at the tip has been designed and tested in the R1Ch wind-tunnel at Mach 3 and under a 0.18 atm static pressure. In the chosen configuration, the shock wave pattern and the flow follow a pulsating mode. The plasma is obtained between the tip and the body of the model by a DC discharge. It was shown possible to synchronize the plasma discharge with the natural pulsating mode of the flow. It was also possible to switch from the aerodynamical pulsating regime to a stable one when obtaining a corona discharge at the model tip using both AC and DC low-power sources. Further investigations of this effect are currently under way and will be reported in a next future.

The second configuration studied in the frame of PUMA deals with the generation of ionic wind superimposed with a subsonic air flow. The purpose is to identify discharges able to interact with boundary layers. Different discharges are considered, such as the corona discharge proposed by Moreau and coll. [2], and the DBD proposed by Roth and coll. [3]. These DC and AC low-energy discharges are able to generate an ionic wind with a maximum amplitude of 3-5 m/s in absence or in presence of a primary flow on a flat plate. Our first efforts have been devoted to develop a physical interpretation of the observed phenomenon as an exchange of momentum between charged particles and neutral molecules of air. Following this interpretation, a very simple theory has been developed and tested to determine whether the amplitude of the ionic wind can be related to the discharge current. The first promising results [4] have encouraged us to develop new experiments as well as introducing more physics in the description of the discharge-flow interaction. The modeling developments are presented in this paper.

2. Interaction between discharges and aerodynamics

Studies have been carried out in the framework of the ionic wind since the early 60's [5]. This phenomenon was first discovered by Hauksbee in 1709.

This could lead to drag reduction or improvement of the atomization in combustion chambers [6]. Basically, it is a mean to provide energy to flows thanks to an electric power supply. This has strong advantages: there is no need for external mass addition and it can act over a wide range of frequencies (0-10 kHz). A lot of experimental works [2], [3], [7]-[9] have pointed out the possibility of reducing drag of about 2-5 %.

In this section, a study of the physical origin of the ionic wind is presented. Then the case of corona discharges is studied.

2.1 Explanation of the ionic wind

When charged species are accelerated by an intense electric field E, they collide with the neutral molecules of the gas. By this mean, they can transfer an amount of their momentum. The force $f_{k\to n}$ that exerts a specie k on a neutral n is:

$$\vec{f}_{k\to n} = m_k N_k \nu_{k-m}\left(\vec{U}_k - \vec{U}_n\right)$$

where m_k is the mass of specie k, N_k its density, U_k its mean velocity. ν_{k-m} is the momentum transfer frequency for collisions between k and n. This expression simplifies because the velocity of charged species are three or four orders of magnitude higher than the neutral velocity. Considering the density current j_k and the mobility μ_k:

$$\vec{j}_k = eN_k\vec{U}_k$$

$$\mu_k = e/m_k\nu_{k-n}$$

and neglecting the diffusion of particles, the total force exerted on the fluid is:

$$\vec{f} = \rho_{ch}\vec{E} = e\left(\sum_{k\ positive} N_k - \sum_{k\ negative} N_k\right)\vec{E}$$

As a consequence, the effect of a plasma on aerodynamics can be strong in regions in which the space charge ρ_{ch} is important.

2.2 Corona discharges

Moreau's team [2], [7] used a wire-to-wire discharge on a flat plate (Figure 1) and observed an ionic wind of 5 m/s.

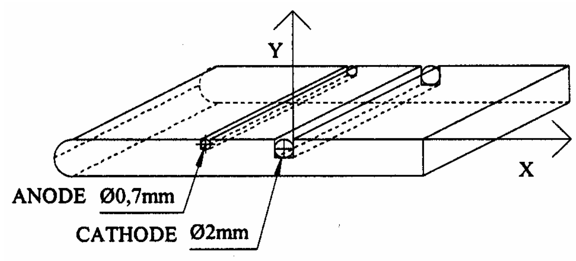

Fig. 1. Experimental setup of Ref. [2]

Two thin electrodes are flushed mounted in a dielectric plate. The first electrode is a 0.7 mm diameter anode set to a +22 kV potential. The second one has a 2 mm diameter and is set to –10 kV. They are distant of 4 cm. The regime of the discharge depends on many parameters such as the potential difference, the space between the electrodes, air humidity degree, flow velocity…etc. From the aerodynamic point of view, the most efficient regime is the corona regime in which a luminescent discharge appears in the vicinity of both electrodes.

The way corona discharges act on the fluid can be explained by focusing on its chemistry. To sum up, a corona appears in the vicinity of an electrode with a fine radius of curvature which is set to a high electric potential. In this region, the electric field created by the electrode is intense. It induces the ionization of neutrals. Electrons are accelerated, they collide with neutrals and if they are energetic enough, they skip an electron out from the neutral. If the electrode is positive, the electrons are rapidly absorbed at the electrode. So there is rapidly no electron to induce any ionization. The streamer theory proposes a physical mechanism which explains how the discharge continues to develop [10], [11]. This theory states that photons created in parallel to the ionization process are able to ionize neutrals in any direction. As a consequence, a short pulse of current is initiated. During this short delay, the large positive space charge exerts a force thanks to the electric field. Moreover, the positive charges drift towards the exterior. This imposes an additional force, much less intense, but on a longer delay time. When the positive charges are evacuated, the conditions for a new pulse are satisfied. Figure 2 sums up this description:

When the electrode is negative, the involved mechanisms are quite different. In the vicinity of the cathode, the electric field initiates ionization. Electrons are evacuated from the cathode. At the same time, electrons are generated from the cathode surface thanks to secondary emission (ionic bombardment, photoemission). When they reach a weaker electric field region, they are attached by the molecules of oxygen so as to create negative ions. If the so-created space charge is sufficient, it counterbalances the external electric field and the discharge disappears. All the charged particles are then evacuated and the conditions for a new ignition are satisfied. This is the phenomenon of Trichel pulses. The pulse frequency is about 10^4-10^6 Hz. Like for the positive discharge, a strong force is exerted during its short growing time, and a weak force during the long evacuation delay. Figure 3 sums up this description.

Another type of discharge used to act on aerodynamics is the dielectric barrier discharge [3], [7], [8]. The advantage of this discharge is the prevention of arcing thanks

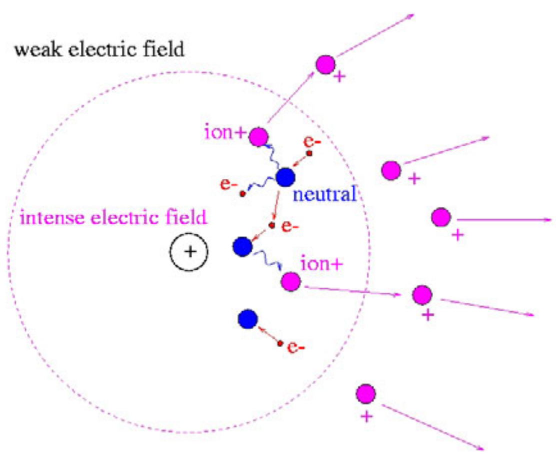

Fig. 2. Ionic wind in positive corona discharges

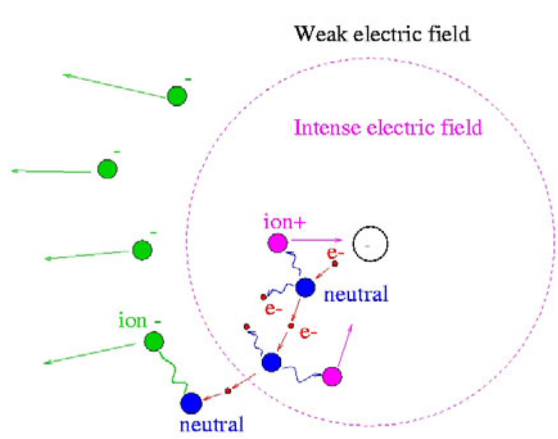

Fig. 3. Ionic wind in negative corona discharges

to a dielectric placed between the electrodes. The action on aerodynamics, explained in [12], is less efficient than coronas but more stable according to [7].

3. Modeling corona discharges / aerodynamics interaction

The present section focuses on the corona actuator such as the one realized by Moreau's team [2] and described above. The equations of the problem are first discussed. Then the numerical method to study the interaction between coronas and flows is detailed.

3.1 Equations

In order to solve the interaction between the flow and the corona discharge, a stable coupling method must be developed. The aerodynamic part follows the momentum equation:

$$\rho\left(\frac{\partial U^i}{\partial t}+U^j\frac{\partial U^i}{\partial x^j}\right)=-\frac{\partial P}{\partial x^i}+\mu\frac{\partial^2 U^i}{\partial x^j\partial x^j}+\rho_{ch}E^i$$

where U^i is the i^{th} component of the flow velocity, ρ is the volumetric mass of air at atmospheric pressure, P is the pressure, μ is the dynamic viscosity of air. Following [13], [14], the discharge is described by the continuity equations for electrons, positive ions, negative ions O_2^- and metastable O_2^* coupled with the Poisson's equation for electric field. Table 1 gives the reactions taken into account in the present work.

Table 1

Corona discharge chemical reactions

Ionization	e, N_2 e, O_2	→ →	e, e, N_2^+ e, e, O_2^+
Photoionization	hν, N_2 hν, O_2	→ →	e, N_2^+ e, O_2^+
Attachment	e, O_2	→	O_2^-
Recombination	e, N_2^+ e, O_2^+ O_2^-, O_2^+ O_2^-, N_2^+	→ → → →	N_2 O_2 O_2, O_2 O_2, N_2
Excitation	e, O_2	→	O_2^*
Detachment	O_2^-, O_2^*	→	e, O_2, O_2
Quenching	O_2, O_2^*	→	O_2, O_2

The kinetics problem is described by the following equations where p stands for positive ions, n for negative ions O_2^-:

$$\frac{\partial N_e}{\partial t}+\frac{\partial N_e U_e^i}{\partial x^i}=S_{ph}+\alpha N_e|U_e|-\eta N_e|U_e|$$
$$-\beta N_e N_p+k_d O_2^* O_2^-$$

$$\frac{\partial N_p}{\partial t}+\frac{\partial N_p U_p^i}{\partial x^i}=S_{ph}+\alpha N_e|U_e|-\beta N_e N_p$$

$$\frac{\partial O_2^-}{\partial t}+\frac{\partial O_2^- U_n^i}{\partial x^i}=\eta N_e|U_e|-\beta O_2^- N_p-k_d O_2^* O_2^-$$

$$\frac{\partial O_2^*}{\partial t}+\frac{\partial O_2^* U^i}{\partial x^i}=\alpha_m N_e|U_e|-k_d O_2^* O_2^-$$

$$\Delta V=-\frac{\rho_{ch}}{\varepsilon_0}$$

α, η, β, α_m, k_d and k_q are respectively the ionization, attachment, recombination, excitement of O_2, detachment of electrons and quenching of O_2^* coefficients. Their values are given by [13], [15] and [18]. ε_0 is the dielectric permittivity. S_{ph} is the photoionization source which, according to [15], follows the equation:

$$S_{ph}=\frac{1}{4\pi}\frac{p_q}{p+p_q}\int_V\frac{S_{ion}(\vec{r_1})}{\left|\vec{r}-\vec{r_1}\right|^2}\psi(\left|\vec{r}-\vec{r_1}\right|^2 p)$$

where p_q is the quenching pressure of the emitting states and set to 30 torr , S_{ion} is the ionization source appearing in the continuity equations for electrons and positive ions, ψ the coefficient of absorption of the ionizing radiation. Kulikovsky in [16] fits the experimental values of ψ obtained by [17] with the model of [15]:

$$\psi(\vec{r_1}-\vec{r_2})=162.2\,\frac{\xi}{4\pi}\frac{1}{p}\frac{p_q}{p+p_q}e^{-119.9\left|\vec{r_1}-\vec{r_2}\right|}$$

The charged particles velocities are composed of the drift velocity due to the electric field and to the transport by the flow:

$$U_k^i=U^i\pm\mu_k E^i$$

The boundary conditions are secondary emission electrons at the cathode by positive ions bombardment. The flux of electrons emitted at the cathode is proportional with the coefficient γ_i to the flux of absorbed ions:

$$N_e = \gamma_i \frac{N_p |U_p|}{|U_e|}$$

3.2 Numerical method

Figure 4 presents the way the two parts of the problem will be coupled. The aerodynamic part is solved thanks to a Fluid Dynamic code developed at ONERA, namely CEDRE. For this calculation, the volumetric force exerted by the discharges is needed. The input data for plasma calculation is the global flow velocity.

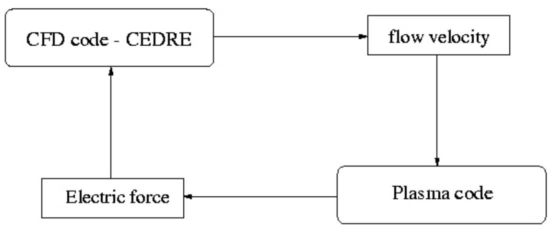

Fig. 4. Principle of plasma / aerodynamics coupling

In order to estimate the action of the plasma on flows, the discharge must be precisely determined. The equations are discretized by a finite volume method. The integration scheme is a 2-step Runge Kutta method in time and a MUSCL flux corrected method. The electric field is calculated thanks to a LU decomposition.

The external electric field is first calculated (Fig. 5) in 2D without any space charge in the (x,y) plane of Figure 1. The anode is located between $x = 2$ cm and $x = 2.07$ cm and the cathode between $x = 5.9$ cm and $x = 6$ cm; both of them are on the dielectric plane $y = 0$.

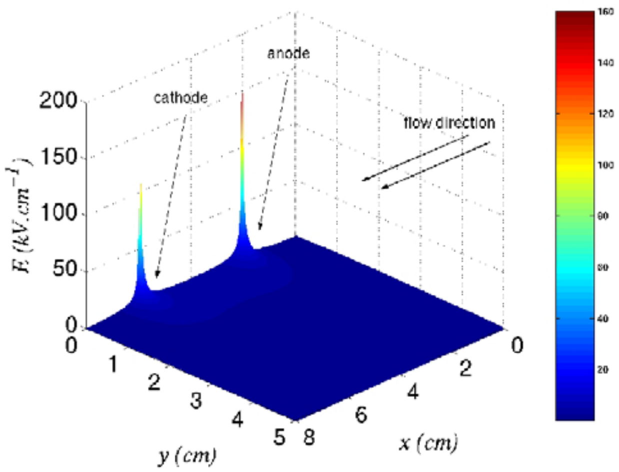

Fig. 5. External electric field in the wire-to-wire configuration

Then the discharge is calculated in 1D along the axis $y = 0$, namely near the surface of the wall where the electrodes are mounted. The mesh grid is uniform with Δx = 40 µm. The final step consists on implementing the force on the 2D CFD code, CEDRE. As the force is calculated in 1D by the plasma module, a model of the discharge expansion in the direction y will be proposed. For instance, the discharge and the force can be supposed to exponentially decrease when y increases.

4. Results

In this section, the results obtained for the negative corona are presented. The domain of calculation extends from $x = 5.7$ cm to the cathode coordinate $x = 5.9$ cm, i.e. on a 2 mm calculation zone length. The mesh is uniform with 50 cells. The physical calculation time is 1 µs, which is expected to be of the order of the delay between two current pulses. The goal is to have a first estimation of the force exerted by the negative discharge. Figure 6 presents the densities of species at different times after the ignition of the discharge. During the first 20 ns, the ionization term induces a fast increase in the electron and ion number densities. The number densities of charged particles rises to 10^{12} cm^{-3}.

The movement of the electrons in the opposite direction of the cathode implies ionization at further locations. A ionizing wave tends to develop. Electrons going faster than ions, a large positive space charge region is created near the cathode. It leads to the modification of the elec-

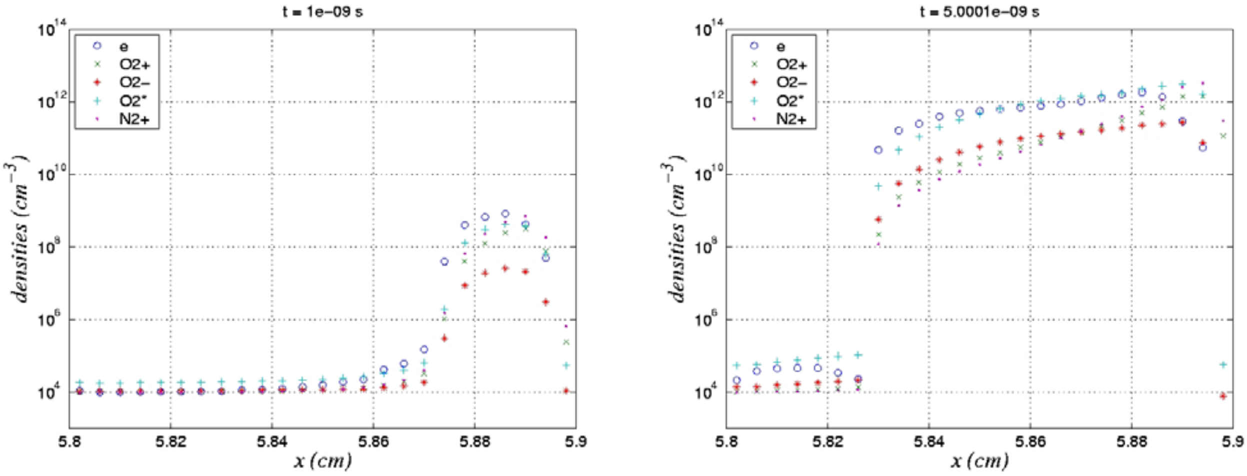

Fig. 6. Species densities at 1 ns and 5 ns

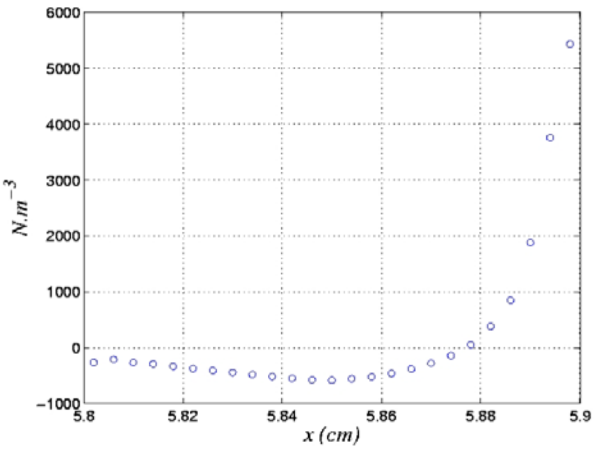

Fig. 7. Electric field at 1 ns, 5 ns and 20 ns

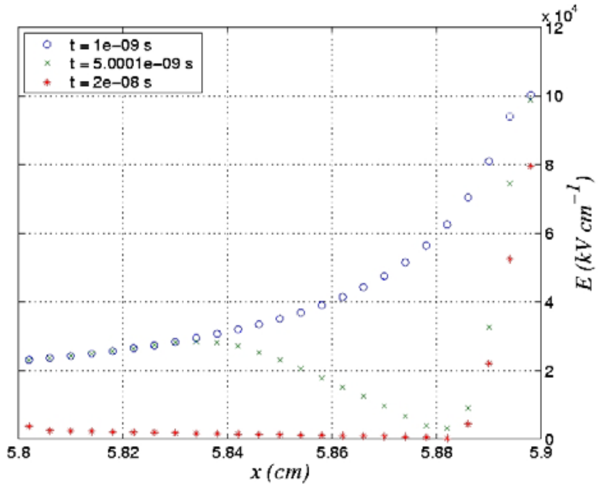

Fig. 8. Mean force between $t = 0$ and $t = 1$ µs

tric field, Figure 7. This space charge combined with an intense electric field induces a maximum force of about 5.10^4 Nm^{-3}. Then the space charge decreases and a smaller force of about 500 Nm^{-3} remains during a longer delay time. When averaged on the total calculation time, i.e. 1 µs, the force exerted on the fluid by the discharge is about 5000 Nm^{-3}, see Figure 8. This extrapolated mean force depends on the supposed delay time between two current pulses. As a consequence, this result is just a first approximation.

However, this approximate value of the force is close to the results of [4] which demonstrates the possibility to act on airflow with such force magnitudes. [12] estimates the force exerted by DBD on fluids to be on the order of 10^3 Nm^{-3}.

5. Conclusion

In order to represent the creation of ionic wind by corona discharges, this paper proposes a simple coupling between a plasma kinetic model and a usual flow model. The first results of the plasma calculation in the vicinity of the cathode show good agreements with previous works. In particular the force exerted by the plasma seems sufficient to explain the ionic wind. In the present work, calculations have been done until $t =$ 1 µs, so that the evolution of the discharge is not entirely described. In the near future, the body force exerted by the wire-to-wire corona discharge will be completely calculated. Then, this force will be implemented in CEDRE to determine the effect on aerodynamics.

References

[1] Elias P Q, Chanetz B, Coponet D, Benay R, Packan D and Larigaldie S. On-board plasma generation in pulsating supersonic flow, *40ème colloque d'aérodynamique appliquée de l'AAAF*, Toulouse, France, 2005.

[2] Léger L, Moreau E and Touchard G. Electrohydrodynamic airflow control along a flat plate by a DC surface corona discharge – Velocity profile and wall pressure measurements. *1st Flow Control Conference*, St. Louis, Missouri, AIAA Paper 2002-2833, 2002.

[3] Roth J R, Sin H, Madhan R and Wilkinson S. Flow re-attachment and acceleration by paraelectric and peristaltic electrohydrodynamic effects. *41st Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, AIAA Paper 2003-531, 2003.

[4] Matéo-Vélez J-C, Thivet F and Degond P. Modélisation élémentaire du vent ionique dans une décharge courone, *4ème Conférence de la Société Française d'Electrostatique*, Poitiers, France, ONERA TP 2004-133, 2004.

[5] Robinson M. Movement of air in the electric wind of the corona discharge. *AIEE Transactions*, New York, USA, 1961.

[6] Larricq C, Lavergne G, Berthoumieu P and Thivet F. Improvement of airblast injectors thanks to electro-aerodynamic actuators. *Proceedings of 2nd NEPCAP*, Sochi, Russia, 2005.

[7] Pons J, Moreau E and Touchard G. Surface DC corona discharges and AC barrier discharges in ambient air at atmospheric pressure. *XV International Conference on Gas Discharges and their Applications,* Toulouse, France, 2004.

[8] Post M L and Corke T C. Plasma actuators for separation control on airfoils. *11th international symposium on flow visualization*, Notre-Dame, Indiana, 2004.

[9] Shcherbakov Y V et al. Drag reduction by AC streamer corona discharges along a wing-like profile plate. *31st AIAA Plasmadynamics and Lasers Conference*, Denver, CO, AIAA Paper 2000-2670, 2000.

[10] F. Massines. *Plasmas froids : génération, caractérisation et technologies*. Publications de l'Université de Saint-Etienne, 2004.

[11] Raizer Y P. *Gas Discharge Physics*. 1st edition, Springer-Verlag, 1991.

[12] Bœuf J-P and Pitchford L. Electrohydrodynamic force and aerodynamic flow acceleration in surface dielectric barrier discharges. *J. Appl. Phys.*, to be published.

[13] Morrow R. The theory of positive glow corona. *J. Phys. D: Appl. Phys.*, Vol. 30, No. 22, pp. 3099-3114, 1997.

[14] Morrow R and Lowke J J. Streamer propagation in air. *J. Phys. D: Appl.Phys.*, Vol. 30, No. 4, pp. 614-627, 1997.

[15] Zhelezniak M B, Mnatsakanian A K H and Sizykh S V. Photoionization of nitrogen and oxygen mixtures by radiation from a gas discharge. *High Temperature*, Vol. 20, No. 3, pp. 357-362, 1982.

[16] Kulikovsky A A. The role of photoionization in positive streamer dynamics. *J. Phys. D: Appl. Phys.*, Vol. 33, No. 12, pp. 1514-1524, 2000.

[17] Penney G W and Hummert G T. Photoionization measurements in air, oxygen, and nitrogen. *J. Appl. Phys.*, Vol. 41, No. 2, pp. 572-577, 1970.

[18] CPAT & Kinema Software, http://www.siglo-kinema.com/bolsig.htm.