Numerical modeling of DC discharges in air flows

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Abstract

This paper deals with the numerical modeling of plasma flow interactions at atmospheric pressure and their application to aerodynamic. A two-dimensional air plasma modeling including complex air kinetic and flow motion is proposed to describe the plasma creation. The net force exerted by the plasma on the flow is introduced in a Navier- Stokes solver to evaluate the modifications of the flow. This model is able to compute pin plate coronas discharges as well as wire to wire.

Key words: plasma flow interaction; corona discharge; drift diffusion model

1. Introduction

In recent years, the study of plasma generations at atmospheric pressure in air has been very active. Several applications are targeted : chemical processing, reduction of gaseous pollutants, material processing... Concerning aeronautics application a great effort has been recently sustained at ONERA to design electromagnetic absorbers and aerodynamic actuators.

New experiments of atmospheric pressure DC discharges have shown the interest of air plasma for aerodynamic flow control. In US, J. R. Roth using barrier dielectric discharges [1] has made it possible to cover the wings and fuselage of aircraft with a thin layer of plasma at low energy cost. He obtain velocities induced (ionic wind) by plasma and observe a significant drag reducing. In France, Moreau's team used a wire to wire corona discharge on a flat plate. They observed a 5 m/s ionic wind in the absence of upcoming flow.

This paper aim to propose a numerical model including plasma generation and coupling with flow motion in order to best understand the physical mechanism responsible of the ionic wind. Numerical results show the ionic wind profile obtained with a wire to wire discharges.

2. Flow and plasma equations

The aerodynamic part of the problem follows the continuum and momentum equations at low Mach number:

$$\frac{\partial U^i}{\partial t} + U^j \frac{\partial U^i}{\partial x_j} + \frac{1}{\rho}\frac{\partial p}{\partial x_i} - \mu \Delta U_i = \frac{f_i}{\rho}, \qquad (1)$$

P is the pressure, ρ the volumetric mass of air, μ the kinetic viscosity , U^i the i^{th} component of the flow velocity and f_i is the force exerted by the plasma on the flow. Following [3], the discharge is described by a simplified model including electrons, positive ions O_2^+, N_2^+, negative ions O_2^- and metastable O_2^*. Ionization,detachment, recombination and quenching are also taken into account. The plasma generation is described by a drift diffusion model (electronic energy is supposed constant), then each charged specie k obey to a mass conservation equation coupled with Poisson's equation :

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$$\frac{\partial n_k}{\partial t} + \frac{\partial j_k^i}{\partial x_i} = K_k, -\frac{\partial^2 V}{\partial x_i \partial x_i} = \frac{\rho_c}{\epsilon_0} \quad (2)$$

where n_k is the density number of the specie k, K_k is the rate production, j_k is the current density of the specie k which is related to the electric field by the Ohm's law $j_k^i = -q_k \mu_k \frac{\partial V}{\partial x_i} + U_i + D_k \frac{\partial n_k}{\partial x_i}$ (where μ_k is the mobility, $\mathcal{D}_k$ isthe diffusion coefficient and q_k is the charge of specie k), V is the electric potential and ρ_c is the net space charge. Secondary electron emission due to ion impacts is also taken into account at the cathode. Finally, a resistance R between the anode and the power supply is V_0. So, the potential difference applied the electrodes is $V_0 - RI$ where I is the total electric current. The electric force is therefore given by $f_i = -\rho_c \frac{\partial V}{\partial x_i}$

3. Algorithm

The time scale of the flow motion is very short with respect the characteristic time of the discharge. Therefore, we consider a one way coupling : the velocity flow remains unchanged during the establishment of the discharge and the plasma is calculated independently of the flow velocity. Then, the force exerted by the plasma f_i is introduced in the Navier-Stokes solver to compute the perturbation produced by the discharge. The set of plasma equation are integrated by an explicit second order (space and time) finite volume scheme using a flux corrected method (MUSCL). Electric potential is solved using a sparse symmetric solver.

4. Results

The configuration we are studying here is the wire to wire experimentation proposed by Moreau and all (see [2]). Two thin electrodes are flushed mounted in a dielectric plate distant of $4cm$. The first electrode is a 0.7 mm diameter anode set to a +22kV potential. The second electrode has 2 mm diameter is set to -10kV. Simulations conditions presented here are the following :$\gamma = 10^{-4}$,inflow velocity $= 0$, $R = 10k\Omega$, mesh grid : 20×400 and time simulation: $1m/s$. One observes a current pulse regime well known in the corona discharges modeling that correlate the current measurements (see reference [2]). The movement of the electrons in the opposite direction of the cathode implies ionization at further locations. A large positive space charge region is produced near the cathode leading to a modification of the electric field . This space charge combined with an intense electric field induces a maximum force of about $510^4 Nm^{-3}$. Then, the space charge decreases and a smaller force remains during a longer delay time. When averaged on the total calculation time, i.e. 1 s, the force exerted on the fluid by the discharge is about $510^3 Nm^{-3}$. In figure 1, the horizontal component of the flow velocitydue to the electric force exerted by the discharge is pictured. The maximum amplitude is about $1.5ms/s$ which is lower than experimental measurements. Nevertheless, the numerical results compare well with qualitative observations : acceleration of the flow at the cathode and increase of the pressure at the anode.

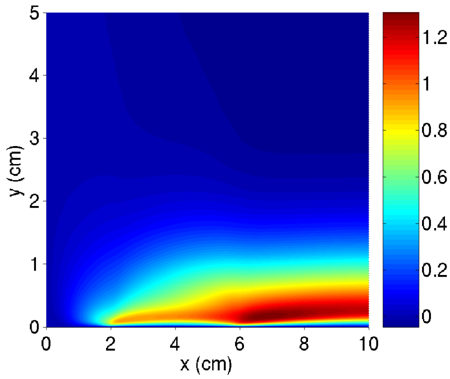

Fig. 1. Ionic wind U_2 (m/s)

5. Summary

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 a qualitative agreement with experimental observations. The force exerted by the discharge seems sufficient to explain the ionic wind.

References

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