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Surface plasma actuators modeling for flow control

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ABSTRACT

The surface plasma actuators over the entire speed region have been intensely investigated for flow control. Most of the fundamental phenomena have been firmly identified by experimental observations but ambiguities still remained. The direct computational simulation for multiple microdischarges is presently beyond our reach, thus the essential physics may be better understood on the framework of physics-based modeling. To achieve this objective, the drift-diffusion approximation is adopted as a transport property approximation to the nonequilibrium air plasma. The most challenging issue of electron impact ionization process at the low-temperature environment is addressed by the Townsend mechanism together with electron attachment, detachment, bulk, and ion–ion recombination. The effects and quantifications of Joule heating, periodic electrostatic force, as well as, the Lorentz acceleration for flow control are examined. The clarification to the hot spot of heat transfer in direct current discharge and the orientations of the periodic force associated with AC cycle of dielectric barrier discharge are also included.

Contents

1. Introduction

During the past decades, sustained research interest and achievements in flow control by aerodynamics–electromagnetics interactions have been remarkable. Numerous innovative techniques have been developed in a wide range of applications from the remote energy deposition, electrical–thermal energy conversion, to surface plasma generation for flow control. However, the surface plasma actuators are the most frequently adopted technique for its simplicity, nonintrusive implementation and control effectiveness [1–5]. The interaction of aerodynamics–electromagnetics is derived from the three basic electromagnetic properties [6,7]: The electrostatic force by the free-space charge separation in the plasma sheath which is the cornerstone of dielectric barrier discharge (DBD) operation. A series of applications devised by Corke et al. [1,2], as well as, Moreau and his colleagues [3] have

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Nomenclature

a	coefficients of the discretized equation
A	matrix of the discretized equation
B	magnetic flux density, Wb/cm^2
C	complementary matrix to A matrix
D	electric displacement, C/cm^2
d_i	diffusion coefficient of charged species i, cm^2/s
e	elemental charge, 1.6002×10^{-19} C
e_i	specific internal energy, erg/g
E	electric field intensity V/cm
F	electrostatic force, dyn/N
h_i	specific enthalpy, erg/g
J	electric current density, A/cm^2
M	matrix for the ILU decomposition
M_i	molecular weight of species I, g mole
n	number density of charge particle, cm^{-3}
p	static pressure, dyn/cm^2
Q	energy transfer between internal degrees of freedom, erg/(s cm^3)
u,v	velocities of gas mixture, cm/s
x,y	components of Cartesian coordinate
α	coefficient of Townsend ionization, cm^{-1}
β	coefficient of recombination, cm^3/s
Γ_I	flux density of spices i, (s cm^2)$^{-1}$
ε	electric permittivity, F/cm
μ_i	mobility of charged species i, cm^2/(s V)
κ	coefficient of detachment, cm^3/s
ρ	density of gas mixture, g/cm^3
ρ_e	electric charge density, C/cm^2
φ	electric field potential, V
ϖ	generation/depletion of species i, g/cm

been successfully demonstrated for flow control at subsonic and transonic flow regimes. The Joule heating occurs for all electrical discharge but it's the dominant effect for direct current discharge (DCD). A glow discharge at a low ambient density becomes Corona discharge at the elevated ambient pressure condition. The thermal plasma actuator is best suited for high altitude flight and closely associated with hypersonic flows [4,5]. The third mechanism for plasma actuator is the Lorentz acceleration which is a cross product of an externally applied magnetic field and the discharge current.

In surface plasma generation by the electron collision process, the Townsend's mechanism controls the secondary emission, multiple primary avalanches, and ultimately maintains the discharge [7,8]. For this reason, the classic Townsend's similarity law for electron impact ionization is still a viable formulation of the complex chemical–physical process to simulate the electrical field dominated phenomena. The charged particle number density is generally limited to an order of magnitude of 10^{12}/cm^3. The generated plasma consists of electrons in a highly excited state but the heavy ions retain the thermodynamic condition of their surrounding environment. Therefore the weakly ionized gas is usually far from thermodynamic equilibrium. Meanwhile the drift motion of charged particles and diffusion, including the ambipolar diffusion, profoundly modifies the transport properties of the ionized medium.

In contrast to DCD, the DBD is maintained by an alternating electric current. The DBD operates on a self-limiting process through the reduced electric field potential by the surface charge accumulation, thus prevents the corona-to-spark transition [7,8]. Specifically, the earlier outstanding effort by Elisson and Kogelschlatz [9] has identified that the discharge consists of two distinct positive Corona streamers and diffusion modes. Enloe et al. [10,11] have reaffirmed that when the exposed electrode is positively biased in the AC cycle, the discharge is characterized by a streamer like structure. These microdischarges have a short life span of about a few nanoseconds and with the random temporal and spatial structures. In the negatively biased phase of the exposed electrode, it acts as the cathode and the discharge appears as a more diffusive structure [9–11]. The discharge pattern over the dielectric surface depends on the polarity and intensity of the applied electric field, as well as, the electric permittivity of the dielectrics [7]. In essence, the propagation of charged particles is in a locked-step to the frequency of the AC field. Meanwhile the induced electrostatic force by the free-space charge separation during the AC cycles becomes a periodic dynamic event. Nevertheless, the discharge phases still can be identified as avalanche, streamer formation, a subsequent glow discharge and finally quenching of the microdischarge on the electrodes [7,8]. A complex physical phenomenon of DBD emerges; a wide range of discharge patterns are observed depending on the gas mixture composition, pressure, electrodes arrangement, and other parameters. However, the global structure always consists of the continuous diffusive and random distributed pulsing microdischarges in a short duration.

An enormous amount of energy is needed to generate localized volumetric plasma that must have a sufficient charged particle number density for strong magneto-aerodynamic interactions [1–5]. For examples, the ionization potential is 34 eV for electron beam [12], 65.7 eV for DCD, and 81 eV per ion–electron pair for discharge at the radio frequency [7,8]. The ionization potential always underestimates the energy requirement in applications, because the nonequilibrium energy cascades to vibration excitation, recombination, and attachment processes. In the electron impact processes for ionization, the positive and negative charged ions still retain their ambient condition. For this reason, the partially ionized is often identified as the low-temperature plasma with a charge number density generally limited to the order of magnitude of 10^{12}/cm^3. As a weakly partial ionized plasma, the electromagnetic force usually exerts a small perturbation to the mainstream flow and the thermodynamic behavior is significantly different from the plasma generated by thermal excitation [7,11]. Therefore the plasma actuator for flow control is the most effective at the flow bifurcations such as the onset of dynamic stall, laminar-turbulent transition, vortical separation [1,2]. However the electromagnetic effect can also be amplified by an externally applied magnetic field or by inviscid–viscous interaction at the leading edge of hypersonic control surfaces [4,5].

The nonequilibrium chemical kinetics associated with the DBD in atmosphere is well known because it had been applied as an ozone generator for years. Elisson et al. [9] have identified plasma chemistry in microdischarge by 30 species through 143 elementary reactions. In a more recent work by Bogdanov et al. [13], the chemical-physics kinetics of atmospheric plasma have been investigated by 576 chemical reactions involving vibrational excitations of nitrogen and oxygen, ozone, positive and negative ions, besides oxide-nitrides. The complexity of the internal degrees of excitations includes molecular nitrogen and oxygen at few quanta above ground states; the atomic nitrogen, ($4S, 2D, 2P$), oxygen (^3P,^1S,^1D), the charged nitrogen molecules ($A^3\Sigma_u^+, B^3\Pi_g, A^1\Pi_g, C^3\Pi_u$) and oxygen ($X^3\Sigma_u^+, A^1\Delta, B^1\Pi$), ozone molecules O_3, as well as, negatively charged ions ($N_2O^-, NO^-, O^-, O_2^-, O_3^-, ..$) and positively charged ions ($N^+, O^+, NO^+, NO_2^+, ..$) respectively. Bogdanov et al.