PHYSICS OF NANOSECOND PULSED PLASMA ACTUATORS

Maryia Nudnova, Svetlana Kindusheva, Nikolay Aleksahdrov,
Moscow Institute of Physics and Technology, Dolgoprudny, RUSSIA
Andrey Starikovskiy
Princeton University, Princeton, USA

Abstract: The paper presents a detailed explanation of the physical mechanism of the nanosecond pulsed surface dielectric barrier discharge (SDBD) effect on the flow. Actuator-induced gas velocities show near-zero values for nanosecond pulses. The measurements performed show overheating in the discharge region at fast ($\tau \sim 1$ μs) thermalization of the plasma inputed energy. The mean values of such heating of the plasma layer can reach 70, 200, and even 400 K for 7-, 12-, and 50-ns pulse durations, respectively. The emerging shock wave together with the secondary vortex flows disturbs the main flow. The resulting pulsed-periodic disturbance causes an efficient transversal momentum transfer into the boundary layer and further flow attachment to the airfoil surface. Thus, for periodic pulsed nanosecond dielectric barrier discharge DBD, the main mechanism of impact is the energy transfer to and heating of the near-surface gas layer. The following pulse-periodic vortex movement stimulates redistribution of the main flow momentum.

1. Introduction

In discharge plasmas, electrons gain energy from an external electric filed and transfer it in collisions into various degrees of freedom of other particles, most of this energy eventually being released into heat. Problems concerning the mechanisms of gas heating in molecular gas discharges have attracted considerable attention in the last decades due to their importance for almost all practical plasmachemical systems. The fast heating leads to significant kinetic changes. Also fast gas heating leads to the instability development for discharge plasmas [1] and glow-to-spark transition [2], favors the propagation of microwave discharges in sub-breakdown electric fields [3] and of leader discharges in ambient air to induce the breakdown of long air gaps and lightning discharges in extremely long gaps [4]. Thus the rate of system thermalization becomes important to operation of gas lasers [1], plasmachemical reactors [5], ozonators, lamps, microelectronics, plasma vapor deposition, surface treatmentand other discharge devices and processes in which the plasma should be uniform. Finally, heat release can play an important role in short-duration pulsed discharges used recently for plasma-assisted ignition of combustible mixtures [6] and for flow control [7,8].

A well-known mechanism of gas heating in molecular gases is the relaxation of vibrationally excited molecules forming a reservoir of energy in discharge plasmas. This process takes sufficiently long (longer than 1 μs at atmospheric pressure air) time. The channels of fast heating in air, molecular nitrogen and some other gases at shorter times have received considerable interest in the last years (see references in [9]). At low (< 20 Td, 1 Td = 10^{-17} V cm^2) reduced electric fields, *E*/*N* (*N* is the gas number density), contribution to fast gas heating is controlled by elastic collisions between electrons and neutral particles and by electron impact rotational excitation of molecules followed by rotational-translational relaxation. At higher values of *E*/*N*, the fraction of electron energy transferred to the translational degrees of freedom of atoms and molecules due to elastic collisions and rotational excitation is less than 3 %. This disagrees with a number of observations in molecular nitrogen, air and other N_2:O_2 mixtures, in which the percentage of fast gas heating was as large as 10-15 % for *E*/*N* > 80 Td (see references in [9]). In this case, the mechanism of fast gas heating was explained by self-quenching reactions of the $N_2(A^3\Sigma_u^+)$ state in pure nitrogen [10, 11, 12] and by electron-impact dissociation of O_2, by quenching of electronically excited N_2 states in collisions with O_2 and by quenching of the $O(^1D)$ state in air and in some other N_2:O_2 mixtures [9]. Computer simulations showed that the fraction of fast heat release increases with increasing electric field due to a growth in the electron energy fraction spent on excitation and dissociation of N_2 and O_2 molecules [9,13].

Recent observations in nanosecond high-voltage discharge [14-18] have shown that fast gas heating may be efficient even at *E*/*N* > 300 Td, when the electron energy fraction spent on excitation and dissociation of the molecules decreases with electric field and most of the electron energy is spent on electron impact ionization. The mechanism of fast gas heating has not been studied at extremely high electric fields, although it has been suggested that this effect is responsible for an extremely high efficiency of operation of aerodynamic plasma actuators using nanosecond pulsed surface dielectric barrier discharges [16,17]. In this case, observations by Starikovskii et al [16] have shown that fast gas heating for several tens degrees leads to a vortex formation in the near-surface gas layer, the mechanism which is opposed to a well-known ion-wind mechanism of plasma actuators based on barrier discharges driven by sinusoidal voltages in the 1-10 kHz range. As a result, the actuators using the nanosecond discharges turned out to be much more efficient over a wide velocity (M = 0.03 – 0.85) and Reynolds number (Re = 10^4 - 2×10^6) ranges. A 2D simulation of the discharge and gas dynamics under conditions similar to those of these experiments has supported these observations [19]. The process of fast plasma thermalization is very important for plasma assisted combustion. Energy release to translational degrees of freedom leads to the hot channels formation and changes the ignition kinetics [20]. This effect can be used to stimulate the breakdown development at high-pressure conditions [21,22]. Fast energy thermalization and gas heating allows to ignite air-fuel mixtures at low initial temperatures and to stimulate distributed multi-spot ignition.