PLASMAS FOR FLOW CONTROL

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1. Introduction

Among all the well-known active methods of flow control, such as mechanical flaps or synthetic jets, a new and original technology using non-thermal surface plasmas is in full expansion. This topic is very new: it merged at the end of the 90' [1]. Plasma actuators consists in using the electric wind produced by the discharge within the boundary layer in order to modify the near-wall flow or to actively interact with the surrounding natural large-scale flow structures. In most of the cases, the actuator is composed by at least two electrodes mounted at the wall of the aerodynamic body shape. Then the high voltage applied between electrodes results in a cold plasma sheet.
In the present course, we focus on the manner to develop and to use plasma actuators. It is divided into four main parts: the first one deals with electrical discharges. The discharge mechanisms are theoretically highlighted and the physical phenomena that results in the electric wind production are described. In the next parts, several types of plasma actuators are presented: the dc surface corona plasma actuator, the single surface dielectric barrier discharge (DBD) actuator and actuators based on DBD or others types of plasmas. During the oral presentation, typical examples of applications of subsonic airflow control by non thermal plasma actuators conducted at University of Poitiers will be accurately described. The results will be analysed and discussed.

2. Electrical discharges : theoretical aspect

2.1. What is a plasma ?

Plasma is the most common phase of matter in the universe. It is composed of positive and negative charged particles in equilibrium, forming an electrically neutral medium. Plasmas are usually named the fourth state of matter because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely. Here we will present plasmas produced by electrical discharges. The electrical gas discharge is a phenomenon observed when a gas becomes electrically conducting because free electric charges can move under the influence of an electric field. The gas is said to be ionized. Ionization is the process of liberating an electron from a particle (atom or molecule), and then the product of ionization is an electron plus a positively charged ion. The number (or concentration) and the velocity (or mobility) of charged particles influence the conductivity of the ionized gas. Plasmas are usually divided into two major categories: thermal and non-thermal ones. Thermal plasma is associated with Joule heating and thermal ionization: their electrical power consumption is high. Non-thermal plasmas operate at low temperature. They may be produced by a variety of electrical discharges, and their particularity is that the majority of the electrical energy goes into the production of energetic electrons instead of heating the gas. More detailed descriptions of non-thermal plasmas at atmospheric pressure may be found in [2] and [3] among others.

2.2. Townsend mechanisms of electrical breakdown

This part introduces briefly the Townsend mechanisms related to electrical breakdown but a more complete description can be found in [3]. Electric breakdown corresponds to the formation of a conductive gas channel that occurs when the electric field exceeds a threshold value. As the result of the breakdown, different types of plasmas may be produced. Although breakdown mechanisms are complex, they are already based on the Townsend mechanism or electron avalanche, which corresponds to the multiplication of some primary electrons in cascade ionization.

Let us consider the simple case of a dc high voltage applied between two plane electrodes with a gap *d*. Then we can assume that some primary electrons are formed at the cathode. Under the electric field, these electrons are accelerated toward the anode and ionizes the gas by collisions with neutral molecules such as $A + e^- \rightarrow A^+ + 2e^-$ where A is a neutral particle and A^+ a positive ion. Then secondary electrons are produced and an avalanche develops because the multiplication of electrons proceeds along their drift from the cathode to the anode. The ionization is traditionally characterized by the Townsend ionization coefficient α which gives the electron production per unit length, or the multiplication of electrons per unit length along the electric field $n_e(x)$:

$$n_e(x) = n_{e0} \times \exp(\alpha x) \tag{1}$$

where n_{e0} is the initial density and x the position between both electrodes. Then each primary electron results in $\exp(\alpha d)-1$ positive ions in the gap if the electron losses due to recombination and attachment to electronegative molecules are neglected. All the $\exp(\alpha d)-1$ positive ions move back to the cathode. This results in the formation of $\gamma \times [\exp(\alpha d)-1]$ electrons from the cathode by the process of secondary electron emission, where γ is the secondary emission coefficient (third Townsend coefficient), corresponding to the probability of a secondary electron generation on the cathode by an ion impact. The secondary electron emission coefficient γ depends on the cathode material, the state of the surface, the type of gas and the reduced electric field. Typical values of γ in electric discharges ranged from 0.01 to 0.1. The discharge current flowing in the electrode gap is self-sustained if $\gamma \times [\exp(\alpha d)-1] = 1$, because positive ions generated by electron avalanche must produce one electron to start a new avalanche.

To ignite a plasma in the electrode gap, the breakdown voltage V_b must be exceeded. V_b may be expressed as follows (Paschen's law):

$$V_b = \frac{A \times p \times d}{\ln[(B \times p \times d)] - \ln[\ln(1 + 1/\gamma)]} \tag{2}$$

with p the pressure, d the electrode gap, A and B constants. For example, in air at normal conditions, $V_b \approx 30$ kV if $d = 1$ cm. One can find this expression as a function of the electric field E_b:

$$\frac{E_b}{p} = \frac{A}{\ln(p \times d) + \ln(B) - \ln[\ln(1 + 1/\gamma)]} \tag{3}$$

with $A = 15$ cm^{-1}.Torr^{-1} and $B = 365$ V.cm^{-1}.Torr^{-1} in air (values of A and B in others gas are given in [3] for instance). As an example, $E_b \approx 30$ kV/cm in air at atmospheric pressure.