Lecture Series Notes for Von Karman Institute Lectures
First Lecture—Keynote Talk

"PLASMA FLOW CONTROL, FUNDAMENTALS, MODELING, AND APPLICATIONS"

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1. INTRODUCTION

Interest in the use of plasmas for the control of air flows has blossomed over the past decades, stimulated to a large degree by two highly innovative concepts. One of the first was the proposal by the Leninetz Holding Company in St. Petersburg, Russia for a new hypersonic, air-breathing aircraft called the AJAX (Gurijanov and Harsha 1996). A diagram of the AJAX concept is shown in Figure 1. Among other features, AJAX proposed the use of magneto-hydrodynamics (MHD) for improved engine performance and a plasma generated air spike to reduce shock strength and thus reduce drag and heat transfer. The second concept was the demonstration of the offset dielectric surface discharge (Roth 2003) which was capable of suppressing separation in low-speed air flows. Figure 2 shows a pair of images taken from Ross 2003 demonstrating the reattachment of an air flow over a wing at an 8 degree angle of attack. The Russian work was an important factor leading to the development of the Weakly Ionized Gas Workshops that were organized in 1997 and continue as part of the American Institute of Aeronautics & Astronautics (AIAA) annual Aerospace Sciences Meeting.

The use of "magneto-aerodynamics" for boundary layer control, heat transfer mitigation, drag reduction and other applications on a reentry vehicle was proposed back in the 1950s (Resler and Sears 1958), and various concepts have been examined in the half century since then (Bushnell 2004). Only recently are some of these concepts now reaching the realm of practicality (Braun et al 2009). A wide range of plasma flow-control opportunities has been suggested, including engine performance enhancement, vehicle-steering, aerodynamic breaking, drag reduction, heat mitigation, shock control, transition suppression, boundary layer separation control, power extraction, lift enhancement, acoustic control, ignition control, flame speed enhancement, and mixing enhancement. Many of these applications were discussed in the review article by Van Wie (2004).

2. Plasma properties

The definition of a plasma is a mixture of ions, electrons and neutral species that has overall charge neutrality. Plasmas are naturally formed at high temperature due to the balance of ionization and electron loss processes at thermal equilibrium. They may also be formed in high electric fields (DC, RF or microwave) where electrons are accelerated to energies high enough to ionize neutrals leading to non-equilibrium ionization by electron impact, which is typical for glow discharge plasmas or plasmas in streamers. The level of ionization is measured by the ratio of the free electron (or ion) density to the density of neutrals, or by the conductivity in Siemens (mhos) per meter. Plasmas of interest for aerodynamic control are weakly ionized, with the ratio of electrons to neutrals less than ~10^{-4} and conductivities on the order of 0.01 to 1 S/m. In air the conductivity at 3000K and at one atmosphere pressure is ~0.02 S/m, but it drops rapidly with temperature and by 2000K it is down to ~8×10^{-7} S/m (Capitelli et al, 2000). To achieve significant conductivities at temperatures lower than 3000K, the air must be seeded with on the order of 1% of an easily ionizable material such as potassium or sodium. In that case significant conductivity can be achieved at temperatures as low as 2000K (~ 0.04 S/m for 1 atmosphere air at 2000K with 1% potassium seeding). For lower temperatures, some external method of sustaining the plasma must be employed. In the AJAX proposal, a nuclear source was suggested, however the electron loss rate through attachment to oxygen in air is so fast (7.6×10^{7}/sec at 1 atm, 30^{0}C) (Dogariu et al 2011) that unacceptable radiation levels would be required. Current methods under consideration include DC electric fields, RF fields, microwaves, lasers, electron beams and short pulsed high voltage electric fields. In some cases, a combination of these methods such as the use of lasers to localize microwaves may be a practical approach.

When the plasma is created by an external source, not only are electrons and ions generated, but the neutral gas is strongly affected. The fundamental mechanism for DC and RF plasma formation is avalanche ionization, which involves electrons accelerated by the electric field colliding with neutrals and forming new ions. An important parameter for the characterization of such externally driven plasmas is the reduced electric field, or the applied electric field divided by the density of molecules, E/N. This is directly proportional to the kinetic energy given to an electron between collisions since the force is the electron charge times the electric field and the distance over which that force is applied is the mean free path, which is equal to the inverse of the product of a collision cross section times the molecular number density. The E/N value reflects the average electron energy, but due to collisions the electrons are distributed in a Maxwell-Boltzmann distribution with the high energy tail of that distribution responsible for ionization. Figure 3 is a classic plot (Raizer 1991) which shows the fraction of energy coupled into various energy modes of air by electron collisions as a function of the reduced electric field. The large cross section for vibrational excitation causes the electron energy distribution to be non Maxwell-Boltzmann, reducing the high energy tail and suppressing the ionization rate. The heating of the gas is immediate for energy deposited into the translational mode and virtually