Lecture Series Notes for Von Karman Institute Lectures
Flow Control Meeting

"LIMITATIONS AND POTENTIAL OF FLOW CONTROL WITH DIELECTRIC BARRIER DISCHARGES"

Richard B. Miles
Department of Mechanical & Aerospace Engineering
PRINCETON UNIVERSITY
Princeton, New Jersey 08544 U.S.A.

Ever since the demonstration by Roth (2003) of the capability for offset surface dielectric barrier discharges to re-attach separated flows, there has been significant interest and widespread research focusing on developing, understanding, and improving the performance of this concept (Corke et al 2010). The primary interest has been the capability of these offset surface dielectric barrier discharges to couple momentum into the flow in proximity of the surface, and, thus, affect the boundary layer. Scaling relationships and phenomenological models have been developed (Thomas et al 2009) that are being used to predict the performance of these dielectric barrier discharges. However, the fundamental physics leading to the momentum transfer and limitations associated with fundamental processes are only now beginning to be understood. In addition, what has become clear is that the coupling to the flow is dependent not only on the momentum transfer, but also on the pulse repetition frequency and on the spacing of dielectric barrier discharge arrays, since these frequencies and spacings couple into natural modes associated with the specific flow field and achieve results similar to those achieved by periodic excitation using other mechanisms (Seifert et al. 1993). In such cases, optimum performance occurs when the pulse repetition or forcing frequency is close to a characteristic flow frequency parameter such as the free stream velocity divided by the length of the separation region. The main difficulty with the surface dielectric barrier discharge flow control concept has been the relatively small interaction force that is generated. Surface jet velocities are typically on the order of a few meters/sec, and, thus, the control of flow fields moving at speeds higher than a few tens of meters/sec has proved elusive. The question then is, can the performance of the dielectric discharge device be significantly improved in order to provide more effective coupling to a wider array of practical flow fields?

To address this question, we must first recognize that the surface dielectric discharge interacts with the flow in two ways. The first is through thermal coupling to the air, and the second is through momentum coupling. The thermal coupling aspects of the device are interesting, since thermal perturbations can also create separation and, in particular, fast coupling can be used to generate shock waves for potential flow control applications (Starikovskii et al 2009). Of more relevance to the discussion here, however, is momentum coupling. Since electrons are very light and carry little momentum, their momentum transfer to the neutral gas is insignificant. Primary momentum transfer comes from the collisions of ions with neutral molecules. For the ions to be affected by an electric field, the plasma must not be charge neutral. For the dielectric barrier discharge configuration, charge separation occurs during the nanosecond time scale dynamics of the plasma formation and the attachment of electrons to oxygen molecules and the attachment of electrons and ions to the surface. A directional force arises from the electric field which is produced by this charge separation. The plasma that is formed is weakly ionized with only on the order of 1-10 ions per million neutrals. In air the electrons attach to oxygen molecules within a few tens of nanoseconds, so shortly after it is formed, the plasma is primarily made up of positive and negative charged ions. As long as the plasma remains charge unbalanced, forcing can be added by the bias voltage. The moving ions form a sort of “porous piston”, driving the neutrals by momentum transfer collisions as the ions are forced through the neutral gas by the potential gradient. Even though the ions may move at relatively high speed, on the order of thousands meters/sec, the overall velocity increase of the bulk neutral gas is only a few meters/sec.

The details of this fundamental mechanism for momentum transfer highlight various limitations associated with dielectric barrier discharge devices. The first is the limitation arising from the duty cycle. The development of charge separation is highly dependent upon the breakdown physics associated with plasma formation. As will be seen shortly, the plasma formation mechanisms are quite different for the positive going half cycle and the negative going half cycle with a sinusoidally-drive dielectric barrier discharge. In addition, the plasma is only formed when the potential is high enough to initiate a breakdown, and, thus, there is “dead time” between these two half-cycle phenomena. This means that the actual time period during which momentum transfer occurs is less than the cycle time of the applied voltage. Various approaches have been undertaken to address this limitation, as will be discussed. The second limitation is associated with the maximum field which can be created. Clearly, the stronger the field, the larger the velocity of the ions and the more momentum coupling that will occur. Once the breakdown process, itself, has created charge separation, the application of the bias further enhances the momentum transfer. However, this bias voltage is limited by air and dielectric breakdown. Approaches to overcome that limitation include the use of very short high-voltage pulses which are turned off before breakdown can occur. It is also apparent from modeling that the plasma formation process leads to velocity components in the forward direction towards the offset electrode, as well as velocity components which are in the backward direction, and the overall momentum transfer is significantly reduced by the backward forcing. Several other effects are not obvious from the momentum transfer argument, including the non-uniformity of the discharge along the electrode edge and the effects of viscous drag on the surface jet.

The basic configuration for the dielectric barrier discharge is shown in Figure 1. It is typically driven by a high voltage sinusoidal field. The discharge is formed along the edge of the exposed