Surface Dielectric Breakdown Plasmas: Introduction

Jake J. Hecla
MIT Rocket Team
3/5/2016

Introduction

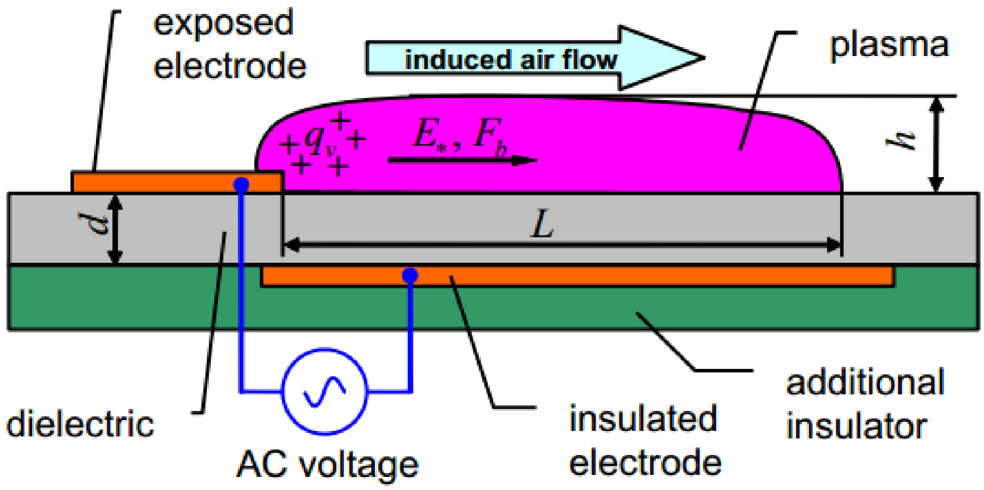
Dielectric barrier discharge (DBD) plasmas have been of interest to the aerospace community since the early 2000s as alternatives to mechanical actuators and boundary-layer suction devices. DBD systems exploit thermal and electrohydrodynamic (EHD) effects to generate airflows ranging from wall jets to turbulent eddies. Though they are relatively energy intensive, DBD systems have shown the ability to drastically alter airfoil flow attachment, boundary layer transition properties and turbulence across a variety of aerodynamic regimes. Tests by NASA in cooperation with Scaled Composites have shown great promise for enhancing flow attachment in high-AOA maneuvers such as those performed by reentering spaceplanes, where they may find a near term implementation. In *Therion*, we hope to explore a different regime of flight by using an array of DBD actuators located on the nose cone and the rocket forebody to investigate changes in skin drag and shockwave behavior.

DBD Plasma Physics

DBD plasmas are atmospheric "glow discharges" that consist of ns-scale self-limiting avalanches generated by time-varying electric fields applied across dielectric materials. DBD plasmas are unusual in that they allow a large amount of current to flow between electrodes in air without the danger of forming a high-temperature arc that could damage the structure to which they are attached.

The canonical DBD electrode consists of a ~5mil kapton film with one conducting strip on either side with an offset of ~1.1 times the chordwise dimension of each conductor (see fig. 1). These electrodes are then excited with a kV-range AC source at 1-100kHz. Lower frequencies (down to 2kHz) seem to offer the highest efficiency because of the suppression of damaging "filament" modes[1]. A corona-like discharge forms between each exposed conductor and the dielectric surface directly above the conductor on the opposite side. However, in contrast to corona discharge, the DBD discharge consists of ~10ns avalanche events. These individual discharges are streamers that carry approximately 100pC of charge each. In the high-pressure regime, these streamers are usually ~100um in diameter, and have current densities that can exceed 1000A/cm^2[2]. Within 10um of both the cathode and the anode, these streamers flare outwards to cover several mm^2, which leads to limited local heating of the conductor. A typical DBD system in air consists of ~10^7 streamers being formed per second.

[1] Kozlov, Alexey. "Plasma actuators for Bluff Body Flow Control." Prospectus for PhD Dissertation. May 2007.
[2] Kogelschatz, Ulrich. "Dielectric-barrier discharges: their history, discharge physics, and industrial applications." *Plasma chemistry and plasma processing* 23.1 (2003): 1-46.



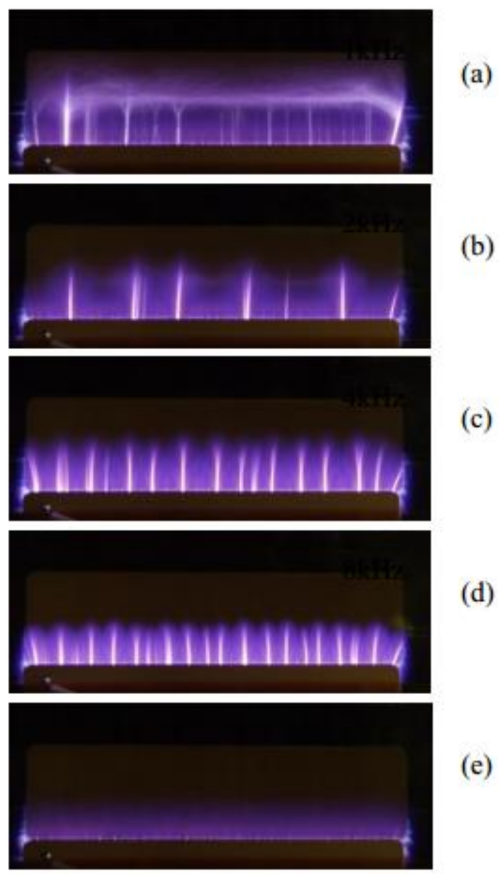


Figure 3.10: Filamentary structure of plasma discharge at various frequencies for 0.125in. quartz glass: (a) 1 kHz, (b) 2 kHz, (c) 4 kHz, (d) 8 kHz, (e) normal discharge at 1 kHz.

Fig.1: [Above] Schematic of a typical SDBD actuator. [Below] Plasma actuator operating in a variety of modes, including the "saturated" filament mode. Taken from Kozlov, 2007

At STP conditions, the typical DBD setup gives purple-hued plasma along with copious amounts of ozone. Pink streamers appear when dV/dt exceeds 10^11v/s[3], though at the cost of reduced electrode lifetime due to greater current density in the streamer channels. This plasma is “cold”, with a mean gas temperature around 350K, and is electrically neutral[4]. Recombination time should be on the order of 10^-8s[5]. Measurements give Te in these gases at around 4-8eV[6] at a density of up to 10^15/cm^3 in the discharge channel. Note that this plasma is in the non-equilibrium regime, meaning that the ion temperature is approximately the neutral gas temperature[7].

Most of the electron energy dissipated in such DBD plasmas goes towards oxygen disassociation, UV generation and the excitation of vibrational modes in N_2[8]. This leaves little energy for electrode heating or damage. Figure 2 below shows an approximate SRIM models of ion damage in the copper electrodes for filament-type breakdown.

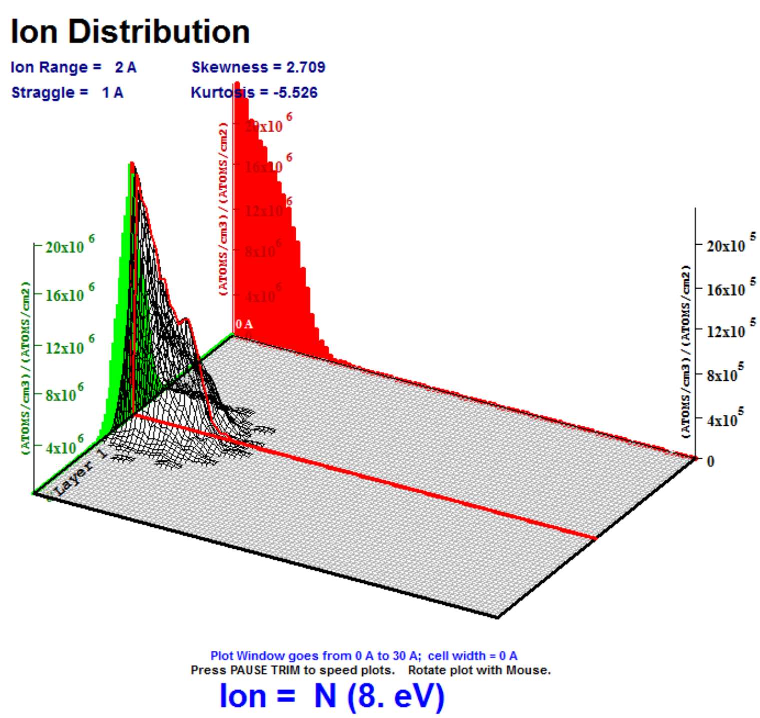


Figure 2: TRIM calculated ion damage tracks for 8eV N ions in Cu. Note that this damage mode is locked out by the non-equilibrium state that the DBD plasma normally occupies. However, the transition to filament breakdown corresponds with the formation of a hotter equilibrium plasma and therefore damage as seen above[9]. Note that kapton is about an order of magnitude less dense and that it <Z> is

[3] Leonov, Sergey, et al. "Supersonic/Transonic Flow Control by Electro-Discharge Plasma Technique." *Proceedings of 25th International Congress of the Aeronautical Sciences*. 2006.
[4] Kogelschatz, “Dielectric barrier discharges”
[5] Kogelschatz, “Dielectric barrier discharges”
[6] Bürkle, Sebastian “Einfluss der Umgebungsbedingung auf Plasma-Aktuatoren mit dielektrischer Barriereentladung” Master-Thesis of B.Sc., B.Sc. Mai 2013.
[7] Bürkle, Sebastian “Plasma-Aktuatoren mit dielektrischer Barriereentladung”
[8] Kogelschatz, “Dielectric barrier discharges”
[9] Schütze, Andreas, et al. "The atmospheric-pressure plasma jet: a review and comparison to other plasma sources." *Plasma Science, IEEE Transactions on* 26.6 (1998): 1685-1694.

significantly lower, which would result in far greater damage for a given ion flux. (Simulation run by author)

DBD Aerodynamic Applications

Past research on surface DBD (SDBD) plasmas has shown that they generate a 1-10m/s jet tangential to the surface on which they are applied. Regardless of the polarity of the discharge, the generated force is along the vector normal to the length of the electrode strips and pointing from the exposed conductor to the dielectric-covered conductor. Various investigations have shown that the velocity perturbation caused by the wall jet scales as V^(7/2), though this is somewhat dependent on the waveform[10]. The resulting force scales linearly with the velocity. Negative-going pulses generate slightly more thrust per unit power, though the mechanism for this is not well understood.

Though the body force is for most purposes quite small, the impact of the flow on the boundary layer is dramatic. Investigations of flow transition along a flat surface by M. N. Kogan showed a 13% increase in the length of the laminar flow region (u_{inf}=10m/s) while using a single relatively weak DBD actuator[11]. This corresponded to a 20% decrease in the skin friction drag over this surface. Investigations at slightly higher velocities (up to 30m/s) show a consistent 10% total drag decrease over semi-streamlined bodies[12]. Full-scale flight tests of aircraft equipped with DBD actuators demonstrate improved flow attachment. In one experiment, a moderate 66.6W/m of input power created a 3% chord increase in turbulent transition distance from the leading edge[13]. The authors posited that this was due to the DBD plasma disrupting the formation of Tollmein-Schlichting waves that catalyze the transition to turbulent flow.

Transonic and supersonic studies have also demonstrated significant effects on flow and shockwave formation. Work by Kelley et. al have shown increases in C_L of up to.30 at Mach .40 using macor dielectrics on a NASA EET airfoil[14]. Using a similar airfoil in a transonic flow, Leonov et. al. showed a ~10% aft shift in the position of the subsonic-supersonic flow transition region [15]. This shows great promise for the application of DBD actuators at very high velocities.

Implications for *Therion*

Though very little research has been done on the application of DBD plasmas to rocketry, the work done so far suggests that DBD electrodes on the rocket forebody may be capable of reducing drag by moving the flow transition point further down. In addition, this may serve to shift the center of pressure aft, improving stability. Depending on the flow velocity to drag reduction dependence (which is not well characterized), this effect may be more pronounced in some flight regimes than others.

---

[10] Enloe, C. L., et al. "Mechanisms and responses of a single dielectric barrier plasma actuator: plasma morphology." *AIAA journal* 42.3 (2004): 589-594.
[11] Kogan, M. N., et al. "Reduction of friction drag by means of boundary layer laminarization using a dielectric barrier discharge." Fluid Dynamics 47.4 (2012): 483-493.
[12] Roy, Subrata, et al. "Dielectric barrier discharge actuator for vehicle drag reduction at highway speeds." *AIP Advances* 6.2 (2016): 025322.
[13] Duchmann, Alexander, et al. "Dielectric barrier discharge plasma actuators for in-flight transition delay." AIAA journal 52.2 (2014): 358-367.
[14] Kelley, Christopher L., et al. "High Mach number leading-edge flow separation control using AC DBD plasma actuators." *AIAA paper* 906 (2012): 2012.
[15] Leonov, Sergey, et al. "Supersonic/Transonic Flow Control."

According to Kozlov, “It has been demonstrated that the thrust due to actuators in series sums approximately linearly and the induced velocity increases greatly.” For our application, this suggests that *Therion* should be equipped with as many DBD strips as we can afford to power. As shown in several of the studies cited here, the drag reduction scales strongly with the flow velocity. If this is accurate, multiple stages should be extremely advantageous.

Future work

The current payload prototype suffers from several issues. The high-power flyback driver runs at >20kHz at the moment, creating a filament-heavy discharge. This should be tuned to drop below 10kHz at worst, which should suppress most of the electrode damage modes. Further, we should take care to increase the dielectric thickness and to reduce the width of the conductors. These changes will bring down the total capacitance and increase our maximum operating voltage.

Main directives:

- Bring the voltage up (20kV+)
- Bring the frequency down (<10kHz)
- Avoid filament mode by smoothing electrode edges
- Bring up battery capacity to eliminate the need for a regulator
- Determine flow behavior and thrust
- Run full-scale, low-speed wind tunnel tests
- Make everyone read: "Airflow control by non-thermal plasma actuators." *Journal of Physics D: Applied Physics* 40.3 (2007): 605. (Moreau, Eric)