WHITEPAPER

VIZGLOW – MODELING OF SPARK-PLUG TRANSIENT PLASMA BREAKDOWN IN AUTOMOTIVE IC ENGINES

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Overview

The arc breakdown phase in automotive spark-plugs is a sub-microsecond event that precedes the main spark event. This phase is typically characterized by strong non-equilibrium plasma phenomena with high voltage and currents. The nature of the initial breakdown phase has strong implications for the successful spark formation and the electrode erosion/lifetime. There are evidently very few studies that seek to characterize this phase in detail. The goal of this work is to investigate this non-equilibrium plasma arc breakdown phase, using high-fidelity computational modeling. We perform studies using the VizGlow™ non-equilibrium plasma modeling tool. During the early breakdown phase, the plasma forms thin filamentary streamers that provide the initial conductive channel across the gap. Once the streamers bridge the gap, the plasma begins to transition to a thermal arc. The redistribution of electrostatic potential across the gap during the breakdown phase causes a large electric field intensification near the cathode. This leads to significant ion bombardment on the electrode surface and fast gas heating, both of which can be attributed to electrode erosion.

Objective

The goal of this work is to address this initial breakdown phase through high-fidelity computational modeling. We address all important aspects of the physical phenomena involved in this phase such as non-equilibrium species generation, fast gas heating, and ion impact at the electrode. Here, we focus only on the initial plasma breakdown phase which typically lasts 10’s of nanoseconds and is characterized by a huge spike in voltage (~10’s of kVs).

Simulation setup

![Simulation setup diagram](image)

Figure 1: Geometry and numerical mesh for the 0.7 mm gap spark plug. The bottom electrode is the powered electrode with the attached circuit. The top electrode is fixed to ground. Each processor is indicated with a different coloring (24 processors total).

A two-dimensional axisymmetric (about y-axis) numerical model of a 0.7 mm gap spark plug in pure air (based on the spark plug gap from Ref. 1) is investigated. The mesh, shown in Figure 1, comprises 150,000
Table 1: Modules used for simulation

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mixed quad/tri cells. The average size of the cells in the gap region is approximately one micron and there are approximately 100,000 cells in the gap between the two electrodes. The minimum grid size is chosen to accurately capture streamer dynamics at length scales comparable to the Debye length of the ensuing plasma.

The total physical time simulated is about 1.75 nanoseconds with a time step of $10^{-14}$ s. This small time step is necessary to resolve the electron dynamics of plasma occurring at the scales of the dielectric relaxation time. The early spark breakdown phase is initiated by applying a high negative polarity voltage on the cathode. For the base case simulation, a supply voltage of -13 kV was applied at the cathode boundary, and the background pressure and temperature was set to 3 bar and 300 K respectively. This applied step voltage is an approximation to the real fast pulse ramp in voltage to initiate breakdown in the inter-electrode gap. The domain was spatially decomposed into partitions with the discrete governing equations in each partition solved using the domain-decomposition parallel computing approach described previously. For the current simulation, 24 processors were used and the total time to completion of 1.75 nanoseconds of simulation time was approximately 30 hours.

**VizGlow™ (Non-equilibrium plasma modeling tool)**

We use VizGlow™, a non-equilibrium plasma modeling tool for this study. VizGlow™ has been utilized previously in the context of streamer discharges for high-pressure combustion,[3] streamer discharges for supersonic combustion ignition,[4] direct-current discharges,[5] and atmospheric pressure plasma jets.[2] The direct-current discharge simulations of Ref. 5 are a quantitative validation of the tool at low pressures with a real experimental system. The atmospheric pressure plasma jet simulations[2] are a qualitative (comparing streamer speeds with experimental observations) validation with experiments at atmospheric pressures. The physics represented in this tool involves solving self-consistent, multi-species, multi-temperature governing equations for the plasma coupled to a compressible Navier-Stokes equation for representation of fluid flow in the system.

**Plasma Model**

Governing differential equations for the production/destruction and transport of multiple charged and neutral species and the electron energy equation, are solved in conjunction with the Poisson’s equation for the self-consistent electrostatic field in the plasma. The photoionization mechanism is an important source of background electrons for streamer propagation in air mixtures and is also accounted for in the model.

**Flow Model**

The compressible Navier-Stokes equations are solved to describe the mean-mass flow velocities, the gas pressure, mass density, and the heavy species (gas) temperature.
Air Chemistry

A plasma chemical kinetic mechanism for air (N$_2$ and O$_2$) is used in this study. The mechanism consists of a total of 11 species (charged and neutrals) with 21 chemical reactions. The species are: electrons (E), O, N$_2$, O$_2$, N$_2^+$, N$_4^+$, O$_2^+$, O$_4^+$, O$^-$, O$_2^-$, O$_2^+$N$_2$. The chemistry mechanism comprises reaction rate pathways from the streamer plasma mechanisms of Refs. 6 and 7. Electron impact reactions for O$_2$ and N$_2$ were generated using the offline Boltzmann solver BOLSIG+$^8$ and the cross-sectional data of Ref. 6 for O$_2$ and N$_2$. Electron impact reactions with oxygen and nitrogen molecules can lead to several different excited energy states: both short lived and long lives. In this mechanism, rotational, vibrational and electronic excited states are not explicitly tracked as separate species. Instead the energy lost to the different rotational, vibrational and electronic excitations are combined into a single electron energy loss pathway. For stationary gas, it is assumed that all energy that leads to excitation of electrons eventually goes to the ground state heavy species energy pool as gas heating.

Results

The step response to a constant voltage pulse on the spark-plug setup was calculated. Electrical circuit transients, plasma structure and species fluxes at the electrode surfaces were obtained. Further, the effect of varying applied voltage on streamer formation process was investigated.

Plasma Structure

The spatial variations of electron number densities are shown in Figure 2. The plasma forms in thin filamentary streamers that originate at the field intensified regions of the electrode tips. The formation of an anode directed (negative) streamer is seen after 0.5 ns at the cathode corner. It is important to note that the evolution of an anode-directed streamer precedes a cathode-directed one because the electric field strength is higher at the cathode corner (Figure 4 top-left) which leads to localized ionization, resulting in the formation of a streamer. This streamer head rapidly propagates towards the anode. At t = 0.9 ns, a cathode directed (positive) streamer is seen to form at the anode corner boundary and moves towards the cathode. At t = 1.0 ns, both the streamer heads merge and the electrode gap is bridged by conductive plasma. Once the electrode gap is bridged, the electron densities continue to rise corresponding to a marked increase in conduction current between the electrodes.

The plasma structure near the cathode surface exhibits distinct phases. Figure 3 shows the evolution of streamers at the cathode boundary. At 0.1 ns, a corona discharge forms in the high E-field region near the electrode corner. A sheath structure surrounding the cathode appears to be fully formed with an electron number density $10^{10}$ per m$^3$. At the same time, an anode-directed streamer appears to originate at the cathode corner. After 0.25 ns, this streamer splits longitudinally into a double streamers – the original anode directed streamer, and a second cathode directed streamer. After around 0.42 ns, the cathode directed streamer impacts the electrode resulting in a spike in conduction current. After this, the anode directed streamer strengthens, and continues to propagate through the spark gap. This complex interaction of the two surface streamers with the cathode sheath results in an amplification of electric field at the cathode boundary, and increases ionic surface flux at the corner.
Figure 2: Electron density (per m$^3$) time snap shots before and after merging of streamers.
Figure 3: Electron density (per $m^3$) time snapshots near the cathode corner.
Figure 4: (TOP) anode and cathode total currents as a function of time; (BOTTOM) cathode conduction, displacement and total current as a function of time.

**Current Transients**

Figure 4 shows the time variation of electrode currents as a function of time. Negligible current is observed to flow through the spark gap, which is highly resistive until about 0.5 ns. At this time, the cathode directed streamer impacts the cathode boundary, thereby causing a current spike. At around 0.9 ms, both the cathode and anode streamers merge. At this instant, the plasma bridges the gap forming a conductive channel and there is a marked increase in the electrode currents. At around 1.0 ns, the channel conductivity increases dramatically indicating transition of streamers to arc.

**Species Flux and Impact Energies**

To quantify damage on the electrode during the non-equilibrium plasma breakdown phase, an important measure is the total flux of ions and their respective impact energies on the electrode surfaces. Figure 5 and Figure 6 show the variation in total wall flux of charged species and their respective energies along the surface of the cathode and anode after 1.5 ns. At the cathode (Figure 5), a region of high electric field covers the corner (radial location of 0.25 mm from axis), which is impacted by positive ions, with the peak number flux of $10^{28}$ particles per m$^2$/s. The wall impact energies for each of the species also peaks at the cathode corner and is around 300 eV for all ions. As the typical sputter threshold energy for metals is around 30 eV or higher,[9] there is a strong potential for damage, in particular due to impinging $O_4^+$ and $N_2^+$ ions.

At the anode corner (Figure 6), the electron wall flux ($\sim10^{28}$ particles per m$^2$/s) is substantially higher than any of the other electrode impacting species. However, the maximum impact energy of all charged species at anode ($\sim10$ eV for $O_2^-$) is substantially lower than at the cathode, and is well below the typical sputter threshold.
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Figure 5: Cathode total wall flux and ion impact energy per molecule for species (N$_2^+$, N$_4^+$, O$_2^+$, and O$_4^+$) at 1.5 ns

Figure 6: Anode total wall flux and ion impact energy per molecule for species (E, O$^-$, and O$_2^-$) at 1.5 ns
energy for metals. Therefore, the effect of ion bombardment on the anode surface damage is predicted to be negligible.

### Sensitivity to Applied Voltage

To investigate the effects of applied voltage on the streamer formation process and the electrical response of the spark plug, several different voltages were applied at the cathode tip boundary and the time for the streamers to bridge the gap was obtained and tabulated below in Figure 7.

An increase in applied voltage accelerates the process of streamer formation and thereby reduces the time taken by the two propagating streamers to bridge the gap. It was also observed that for voltages less than 11 kV, plasma breakdown did not occur in 2 nanoseconds (although streamer formation may still occur after a longer time or may take the form of a volumetric corona discharge).

### References


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