WHITEPAPER

VIZGLOW – FAST PREDICTIVE MODELING OF BREAKDOWN PHENOMENA IN AN AUTOMOTIVE SPARK PLUG

(Published June 4, 2020)

EsgeeTechnologies Inc.
Analysis and Design through High-Fidelity Simulations

Overview

The electrical breakdown of a spark gap is the first step in the lifecycle of a single spark discharge event. This breakdown is achieved by a large initial voltage spike that induces corona discharge at the high-voltage electrode followed by a streamer formation that bridges the gap and finally evolves into a thermal (spark). The voltage required for breakdown depends on the inter-electrode gap, the gas pressure, gas type, and electrode shape among other factors. In a practical spark-plug device the electrodes erode over time, smoothening sharp electrode corners, and increasing the inter-electrode gap size thereby increasing the breakdown voltage requirements. Eventually, after long term use the electrode erosion can be such that the pulse forming circuit (e.g. ignition coil) that drives the breakdown and spark formation cannot provide the minimum voltage for breakdown. The spark-plug is then no longer usable. In lieu of spark-plug lifetime experiments, high-fidelity numerical models that can be used to analyze the breakdown of the gas using full physics representation of the plasma, the electrostatic fields, and electrode surface physics that all play in role in the breakdown phenomena. In this work, we present a fast, predictive breakdown model that blends the speed and computational efficiency of a simplified phenomenological model and while incorporating the essential physics of the breakdown event. The breakdown model is incorporated into our multi-physics non-equilibrium plasma software package *VizGlow*™.

Objective

The objective of the present study is to demonstrate the breakdown effectiveness of a spark plug configuration using the special predictive breakdown model available in *VizGlow*™. We present simulations of a two-dimensional spark plug configuration using the breakdown model and compare it with the full-fidelity plasma simulation using *VizGlow*™. We demonstrate the effectiveness of breakdown model plugin in predicting the onset of plasma breakdown and spark channel formation at a fractional computational cost as compared to the full-fidelity plasma simulation.

Simulation setup

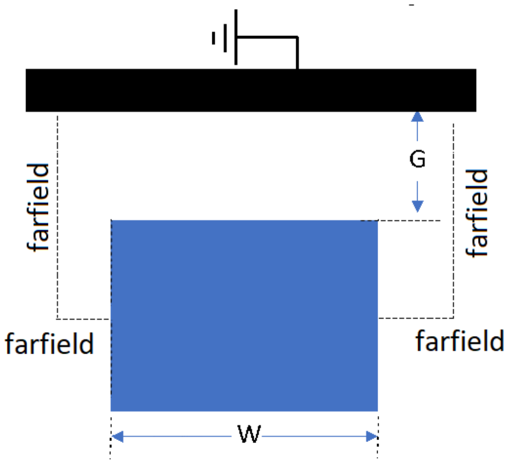

Figure 1: Pin-to-plane configuration used for 2D parametric electric field and breakdown simulations.

Table 1: Modules used for simulation

Module	Description
Non-Equilibrium Plasma	Two-temperature cold plasma model

A pin-to-plane electrode geometry of a spark plug, as shown in Figure 1, is used. The plane is grounded and the surrounding regions are modeled as electrical far-field boundaries. The gas mixture is air, with a pressure of 10 bar and a temperature of 700 K. The pin electrode voltage is varied from -10 kV to -15 kV. The plane is fixed as ground (0 kV). The full fidelity plasma model resolves the plasma formation from the initial application of the pulse at t=0 to a simulation time of t=5 nanoseconds. The voltage is applied as a constant voltage at the pin electrode. The breakdown model utilizes the same gas conditions and voltages as the full-fidelity plasma model.

A spark discharge is preceded by a transient filamentary streamer discharge. Hence, in order to evaluate the breakdown effectiveness of a spark plug, it is important to predict the formation of the streamer discharge. *VizGlow*™ is used in the present study to perform detailed full-fidelity plasma simulation for a reactive gas. *VizGlow*™ has been utilized previously in the context of gap breakdown for spark plug like geometry.[1]

Table 2: Ionization integral range estimates for when streamer breakdown occurs in air from experimental studies and numerical simulations.

Reference	k_0 for air
Nasser and Heiszler[2]	9.9-13
Hartman[3]	7-14
Raether-Meeks[4, 5]	20
Zaengl and Petcharakas[6]	9
Lowke[7]	9.2
Mikropoulos[8]	8-18
Naidis[9]	7-16
Chvyreva et al.[10]	16.7-22.7

The full-fidelity plasma simulation involves solving governing differential equations for the production/destruction and transport of multiple charged and neutral species and the electron energy equation, in conjunction with the Poisson's equation for the self-consistent electrostatic potential 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.

Results

The breakdown prediction model relates the probability of the streamer breakdown at a spatial location as a function of the electric field at the location, gas pressure and the net ionization coefficient at the location. The

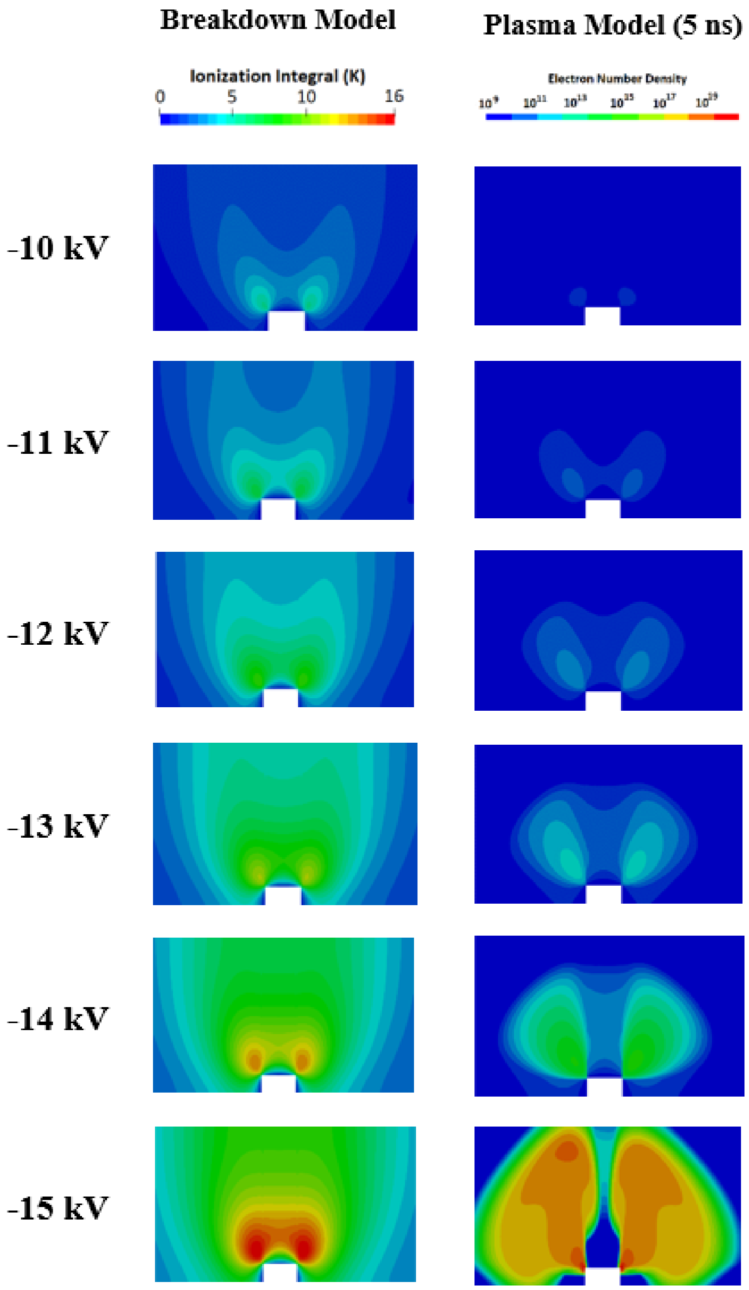

Figure 2: Comparison of ionization integral values from breakdown model (left) compared with plasma densities from full-fidelity plasma model after 5 nanoseconds (right).

model generates a scalar breakdown probability (K), termed as the ionization integral, which can be interpreted as a probability or likelihood that plasma breakdown will occur at that location. The breakdown probability is high when the ionization integral exceeds a certain threshold value K_0, which depends on the gas mixture. The K_0 for plasma breakdown onset in air has been measured experimentally and numerically by several different authors and are tabulated in Table 2. In air for weakly non-homogeneous fields, the threshold streamer integral is in the range $K_0 = 16 - 22$.

The chief advantage of using the breakdown model plugin is that it is nearly as efficient as vacuum electric field simulations, takes only a fractional of computational cost as compared to full-fidelity plasma simulation, yet takes into account additional physical phenomena such as ionization reaction processes and gas pressure.

The results for the full-fidelity plasma model and the breakdown model are compared side-by-side in Figure 2. The breakdown model ionization integral (K) is shown on the left column while the plasma (electron) particle number density is shown on the right column. For the given pressure, temperature and voltage range, the ionization integral near the edges of the pin lies between 0-16. Recall from Table 2 that the K-factor range where streamer breakdown is expected to occur is from 10-20. For the pin-to-plane geometry investigated here, the K-factor is below 10 for pin voltages of -10 kV to -12 kV. The plasma forms as a weak corona with electron densities below 10^{12} m^{-3} (compared to the background air density of 10^{26} m^{-3}). At -13 kV, the K-factor peak is 12 and the plasma density has increased by several orders of magnitude to 10^{14} m^{-3}. At -14 kV the K factor is 15 and densities are again orders of magnitude higher although the plasma is still corona-like (diffused plasma constricted near the electrodes). At -15 kV, the K-factor reaches over 16 and we can see a sharp increase in the number density of the plasma (10^{20} m^{-3}) and a full bridging of the gap indicating plasma breakdown in the inter-electrode gap. From these results, we conclude that our full-fidelity plasma model predicts gap breakdown for the pin-to-plane geometry for K-factor around 16 which is in good agreement with observations from experiments and simulations from other authors listed in Table 2. The full fidelity plasma simulation model simulates 5 nanoseconds of time using timesteps of 10^{-13} s, hence requiring 50,000 computational timesteps. The breakdown model requires approximately the same amount of numerical effort per computational step but only a single “timestep” is required. The computational savings are obvious.

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