SAND2016-11639D

Calorimetry and Imaging of Plasma Produced by a Pulsed Nanosecond Discharge Igniter in EGR Gases at Engine-Relevant Conditions

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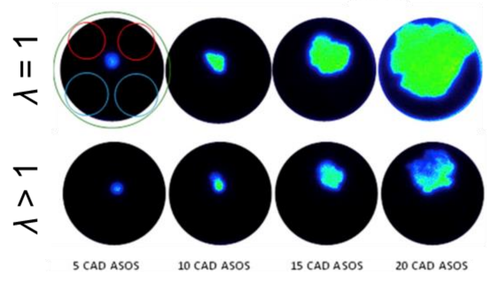
Abstract

Pulsed nanosecond discharges (PND) can achieve ignition in internal combustion (IC) engines through enhanced reaction kinetics as a result of elevated electron energies without the associated increases in translational gas temperature that cause electrode erosion. PND can improve tolerance to exhaust gas recirculation (EGR), which is used to increase engine efficiency and reduce emissions. Atomic oxygen (O), including its electronically excited states, is thought to be a key species in promoting low-temperature ignition. In this work, high-voltage PND are examined in EGR-like mixtures (oxygen/nitrogen/carbon dioxide) at engine-relevant number densities (up to 9 bar at 70°C) through pressure-rise calorimetry and direct imaging of excited state O-atom (O^*) in an optically accessible spark calorimeter.

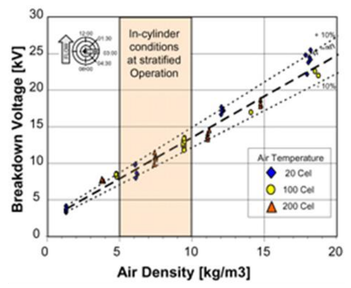
Traditional inductive spark ignition systems have struggled with next-generation gasoline IC engines due to:

Slow flame kernel growth in dilute charge mixtures (air or EGR dilution)



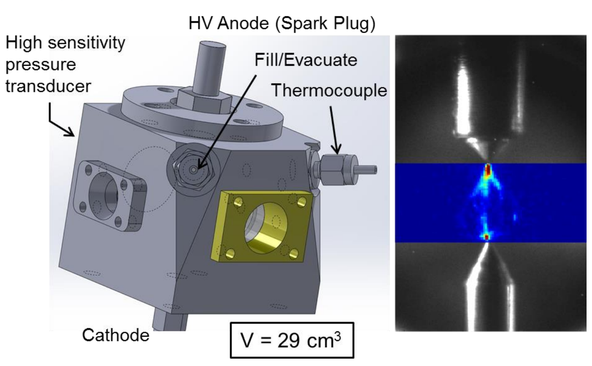
S. Merola, et al, Energy, 2016; 108:50-62.

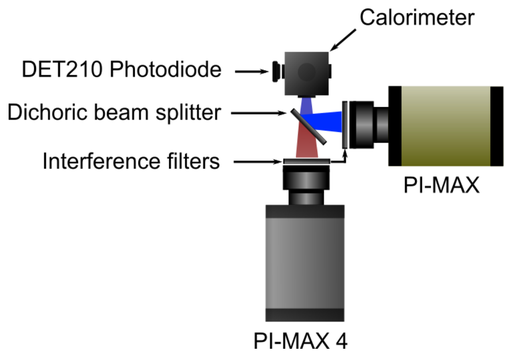
High breakdown voltages needed for elevated charge densities & large electrode-gap distances

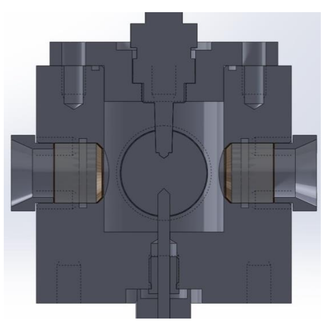


Piock et al, SAE Int J Engines, 2010;3:389-401.

Fundamental experiments provided insights into LTP and SSB discharges.







Initial Temperature [°C]	Calorimetry: 70 ± 1.0, Imaging: 21 ± 1.0
Initial Pressure [bar]	1.07 – 9.0
Inter-Electrode Distance [mm]	5.0, Anode Only (tip radius of curv. ≈ 125 µm)
Gas Mixtures [mole-%] †‡	Ultra-air: 21.9% O_2, 78.1% N_2 (γ = 1.397) 15.9% O_2, 84.1% N_2 (γ = 1.397) 15.9% O_2, 78.8% N_2, 5.3% CO_2 (γ = 1.387)

†All ratio of specific heats (γ) calculated at 70 °C.
‡Additional minor species in ultra-air neglected.

Next-gen. IC engine ignition: low-temperature plasma (LTP) is desirable, but secondary streamer breakdown (SSB) is not. What's the difference?

1. Primary streamer phase

+ 10's of kV

Ionization by primary streamer head. Electrons move towards anode leaving positive space charge in streamer path; reduces potential drop near anode.

Δt ~ $\mathcal{O}$(1 ns)

- GND

2. Compensation phase

Primary streamer connects to cathode. Negative charge flows from cathode to compensate positive space charge, often called "return wave". E-field increases near anode, decreases near cathode.

3.Secondary streamer phase — **LTP**

Secondary streamer advances. Strong E-field near anode leads to rapid advance, more slowly as approaches weaker E-field near cathode. High rate of attachment prevents arc transition.

Δt ~ $\mathcal{O}$(10 ns)

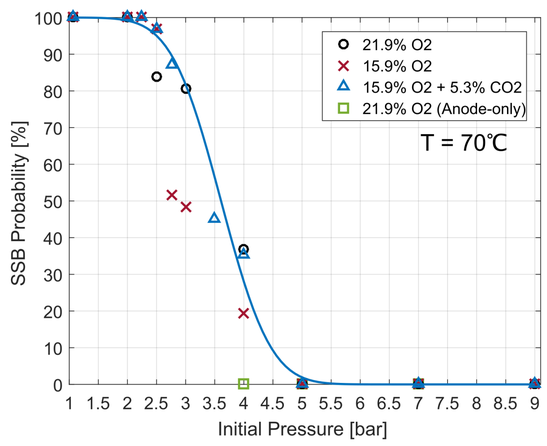
SSB

4. Transient arc phase

Arc occurs if secondary streamer reaches cathode (*E*/*N* high along the entire discharge filament). Secondary streamer propagation promoted by local heating from V-T relaxation (reduction in *N*).

SSB » increased electrode erosion

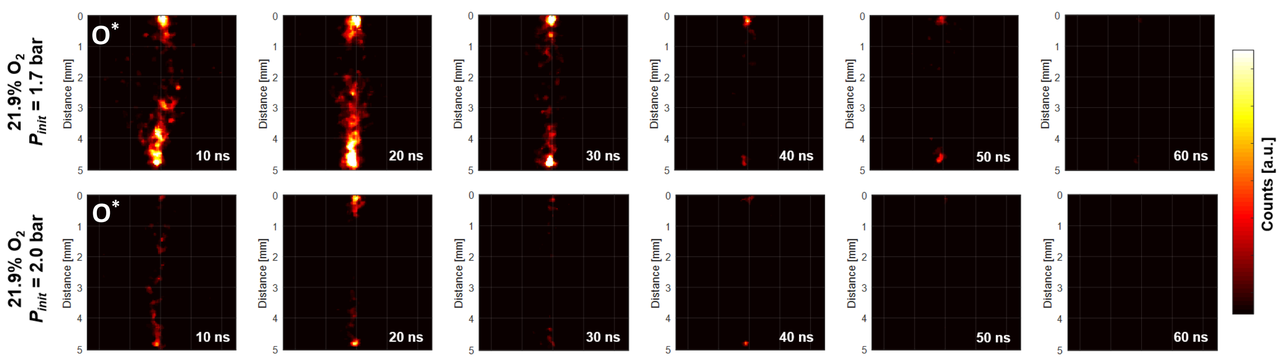
SSB occurrence probability decreased as pressure was increased. Dependence on gas composition was small.



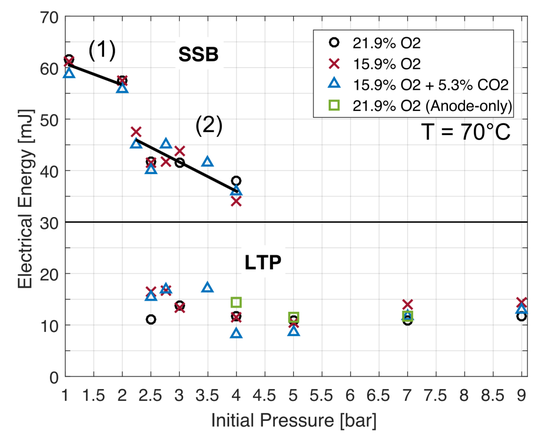
As pressure increased, secondary streamer velocity decreased. The secondary streamer did not reach the cathode rapidly enough for SSB to occur.

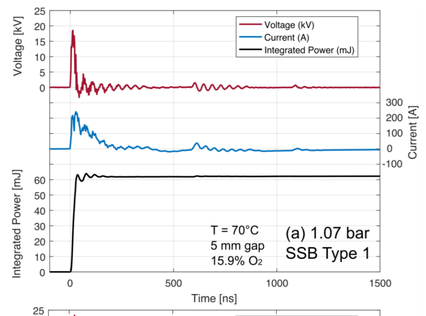
Removing the cathode (i.e. "Anode-only") also reduced SSB probability: from ~30% to zero at P_{init} = 4 bar.

Single-shot images of O^* emission: signal concentrated near anode/cathode tips. One advantage of cathode is increased radical production.



The character of the SSB discharges changed as pressure was increased: breakdown occurred later, including during the reflected pulse. The impact on pulse energy and electrical-to-thermal energy conversion efficiency was apparent.





Entire-discharge mean images show mixture dependence of O^* emission. Impact of CO_2 not explained by changes in quenching or electron energy.

Conclusions

Considering EGR effects on PND:

- PND calorimetry did not depend appreciably on CO_2 or O_2 concentration in the range considered.
- Addition of CO_2 reduced O^* signal, likely through a chemical pathway.
- A cathode was found to be beneficial for O^* production, at the expense of increased SSB probability at certain conditions.

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