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Streamer-to-spark transition initiated by a nanosecond overvoltage pulsed discharge in air

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Combustion engines operated in very lean mixture conditions at high load and high Exhaust Gas Recirculation (EGR) rate are essential for good efficiency as well as for meeting fuel consumption reduction and CO₂ emission standards. In such conditions, it is important to increase the performance of ignition systems to guarantee a successful ignition. The main key parameters of an ignition system are the amount of energy loaded to the gas, the volume and duration of such energy deposition. Thus, two ignition systems can be considered based on whether the energy is deposited during a short time (nanosecond ignition system,) or large time (millisecond system such as standard coil system).

For a standard ignition system, the energy transferred to the gas is essentially thermal with energy deposition duration in few of milliseconds involving high electrode losses. For a nanosecond ignition system, the spark is preceded by a streamer during which the main part of the energy is transferred very efficiently to the vibrational and electronic excitation modes of the gas molecules [1]. The physical processes involved during the transition between the streamer to the spark are not well understood [2]. Therefore, space and time-resolved experimental data of the gas temperature during the streamer phase, the electron temperature and density during the spark phase are required for quantitative insight into plasma-assisted ignition.

The discharge setup consists in a pin-to-pin geometry with an interelectrode gap of 3 mm and a tip curvature of radius 150 μm . The discharge is generated in atmospheric pressure air by application of a positive high voltage pulse of 40 kV, 25 ns width and a rise time of 5 ns at the repetition rate of 10 Hz. The discharge generated consists of a streamer phase with high voltage and high current followed by a spark phase characterized by a decreasing current in several hundred of nanosecond. The deposited energy is about 54 mJ per pulsed discharge. Space and time-resolved OES is used to measure firstly, the gas temperature from the second positive system of nitrogen during the streamer phase, and secondly, the electron number density and temperature from the singly ionized nitrogen lines during the spark phase. Supplementary data, such as the gas temperature and the vibrational temperature of nitrogen molecules in their ground state are also measured in the gas surrounding the spark using spontaneous Raman scattering.

Results show an ultra-fast gas heating up to 1200 K on the axis of the discharge streamer channel at 15 ns after the current rise. This ultra-fast gas heating due to the quenching of electronically excited species by oxygen molecules is followed by a fast dissociation of molecules and then the streamer transits to spark characterized by a high degree of ionization of nitrogen and oxygen atoms. As a consequence, the electron density (n_e) and temperature (T_e) reached $90 \times 10^{17} \text{cm}^{-3}$ and 45000 K respectively at 20 ns after the current rise. The expansion of the generated strong shock wave, leads a decrease in both $n_e = 8 \times 10^{17} \text{cm}^{-3}$ and $T_e = 27000 \text{K}$ at 350 ns. In the gas surrounding the spark ($r = 1250 \mu\text{m}$), a rapid increase in the vibrational temperature of nitrogen molecules is observed ($t > 1 \mu\text{s}$) result of the shock wave-induced convective transport [3, 4] of the remaining vibrational excited nitrogen molecules produced by the streamer.

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