Spark Plug and Corona Abilities to Ignite Lean Methane/Air Mixtures

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Introduction

Corona discharge in gases has many applications in plasma reactors, ozone generation, anti-pollution systems, etc. One of the most interesting practical applications is the use of corona discharge for the ignition of combustible mixtures in engines. A short pulsed corona was used first by Liu et al. (2002) for the ignition of CH_4-air mixtures. As mentioned in this work, potential advantages of corona ignition are the following. A corona has a better coupling with the gas because the cross-section for dissociation and ionization more closely matches the electron energy distribution function in the discharge. Corona discharge also has lower energy losses through lower radiation and lower anode and cathode losses. It is worth noting that a corona produces numerous streamers, each of which has similar energy content, as opposed to a single, unnecessarily large and intense arc. Moreover, a corona allows initiation of combustion in a large volume; the ignition volume can be tailored using the anode and cathode geometry. Finally, a corona generates a gas flow (corona wind) characterized by intensive turbulence. For nanosecond or microsecond duration discharge, the corona wind is negligible, whereas for a millisecond pulsed corona, the corona wind starts to be significant (Bellenoue[a)], 2004). Generated by a corona discharge, turbulent gas flow influences the initial flame kernel development positively. Due to the characteristics mentioned above, the use of corona discharge for ignition of combustible mixtures looks very attractive.

Currently, there are only a few studies related to corona ignition (Liu, 2002; Starikovskii, 2003, Bellenoue[b)], 2004). In these works, some advantages of pulsed corona ignition over spark plug ignition have been demonstrated. The scarcity of experimental data does not allow comparative analysis of spark plug and corona ignition efficiency and the determination of the corona ignition mechanism. In this work, spark plugs and coronas have been used for the ignition of extremely lean fuel methane/air mixtures. Energetic efficiency and ignition ability have been analysed for these ignition systems.

Experimental set-up

In our experiments, a quiescent premixed methane/air mixture of equivalence ratios 0.55 or 0.517 is ignited by a spark plug or positive corona. Experiments are carried out with an initial pressure of 0.15 MPa. Combustion occurs in a cylindrical combustion chamber of 80 mm in diameter and 30 mm in height. Glass windows mounted on the side-wall of the chamber allow observation of all cross-sections of the combustion vessel. The same electrodes have been used for spark and corona ignition. One of the discharge electrodes (constantan wire of 0.35 mm in diameter, lateral surface of the wire is covered by Teflon isolation) is placed along the axis of symmetry of the combustion chamber. The chamber wall is used as another discharge electrode. In all tests, the discharge gap is 20 mm.

In spark plug ignition tests, capacitive discharge is used. The spark plug ignition unit is based on the high voltage converter coil allowing a voltage up to 25 kV across the discharge gap. Discharge energy stored in the ignition system is controlled by the value of the capacitor discharging through the primary circuit. In our tests, the value of the maximal energy stored is 80 mJ, the duration of the discharge is about 50-100 μs, the peak discharge current value is 16-16.5 A, and the discharge energy is 16-17 mJ.

An *Entwicklung Leistungselectronik* type power supply is used to generate the corona discharge in single pulse mode. In our experiments, positive corona pulse durations of 3 ms, 10 ms, and 20 ms have been used for ignition. Depending on the discharge duration, the discharge energy igniting the combustible mixture varies in the range of 0.5-0.7 mJ.

Two diagnostics have been used to study the ignition and to follow the flame kernel development. One is the record of pressure time evolution during combustion. The *dP/dt* value obtained from the pressure signal is used as the characteristic of combustion efficiency. Another diagnostic used is Schlieren visualization of the combustion process. A Kodak camera (Kodak Ektapro HS Motion Analyser) performing 500-40500 frames/s has been used for Schlieren image recording. A continuous wave Ar laser supplied by a break cell producing highlight pulses of 3 μs in duration is used as a light source.

Results

Schlieren snapshots of spark plug and corona ignition of a 0.55 equivalence ratio mixture are shown in Fig. 1 and Fig. 2, respectively. It appears that the spark ignites the combustible mixture simultaneously in all cross-sections of the spark gap (see Fig. 1). It is worth noting that ignition occurs at the last stage of the discharge, when the plasma is rather cold. Non-straight line spark shape causes initial flame front wrinkling.

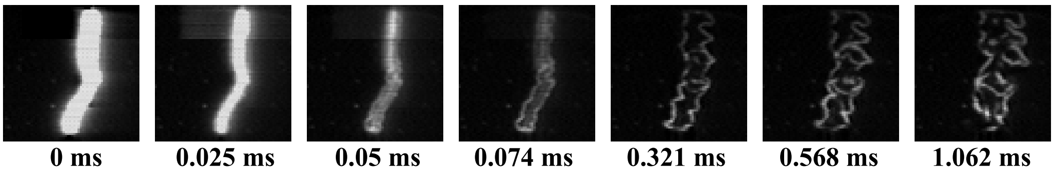

Figure 1. Spark plug ignition of CH_4/Air mixture of equivalence ratio 0.55.

In Fig. 2, Schlieren snapshots of corona ignition of the same mixture for discharge duration of 3 ms are shown with corresponding oscilloscope traces of the corona discharge trigger signal (curve “a”), voltage across the gap (curve “b”), and discharge current (curve “c”). Dashed vertical lines in oscilloscope traces mark the time instants when corresponding Schlieren images have been obtained. It can be seen that corona streamer discharge is characterised by a brush of current pulses of 0.5-2 mA in amplitude. At the beginning of the discharge no change in mixture density across the discharge gap has been recorded. The first changes in gas density can be observed in the anode region 2.5 ms after the beginning of the discharge. Our preliminary tests carried out in Argon at the same discharge parameters (discharge current and corona pulse duration) and using the same Schlieren optical scheme does not detect the gas heating in the discharge. Thus, the change in gas density observed in the combustible mixture is due to the mixture decomposition in the corona. The Schlieren image in Fig. 2 corresponding to 2.83 ms shows that the brightness of some spots in the discharge area are comparable to the brightness of the flame front (see following images). Nevertheless, it is difficult to make a definite conclusion about spot ignition at this stage. Future investigations are necessary in order to determine the ignition instant and locations of initial combustion zones. A snapshot corresponding to 2.85 ms (see Fig. 2) shows that the gas area modified by the discharge acts as an electrical conductive channel for the development of a streamer (or low current spark) passing the discharge gap and igniting the combustible mixture similar to a conventional spark. It is worth noting that, for corona ignition, the total energy of the discharge (corona + igniting streamer) is about 20-25 times less than the discharge energy for the case of spark plug ignition.

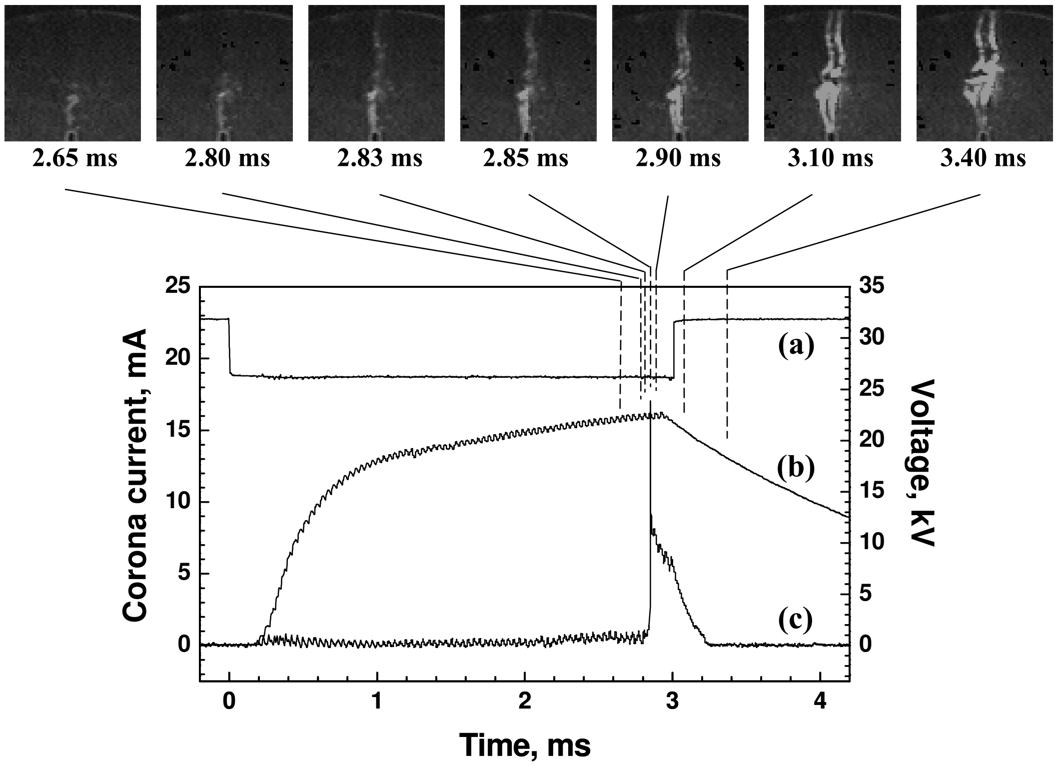

Figure 2. Schlieren snapshots of corona development and typical oscilloscope traces of discharge trigger signal (a), discharge gap voltage (b), and corona current (c). Trigger signal is given in arbitrary units. Discharge duration is 3 ms. CH_4/Air mixture of equivalence ratio 0.55. Beginning of time scale corresponds to discharge switching on.

It was found that for 0.55 equivalence ratio mixture there is no difference in the combustion time (time to obtain maximum pressure) and in the rate of pressure growth when ignition by a spark plug or corona of 3 ms duration has been used. Ignition by a longer corona pulse decreases the combustion time from 290 ms (spark plug ignition) to 250-270 ms, depending on the corona pulse duration. A decrease of combustion time is accompanied by an increase of maximum pressure due to less wall heat losses. The positive influence of the corona pulse duration is related to an increase of mixture treatment time and generation of higher turbulence intensity near the electrodes which promotes the combustion. For the case of ignition by a corona of 20 ms duration, the rate of pressure growth *dP/dt* at the middle stage of combustion is about twice as high as that for spark plug ignition.

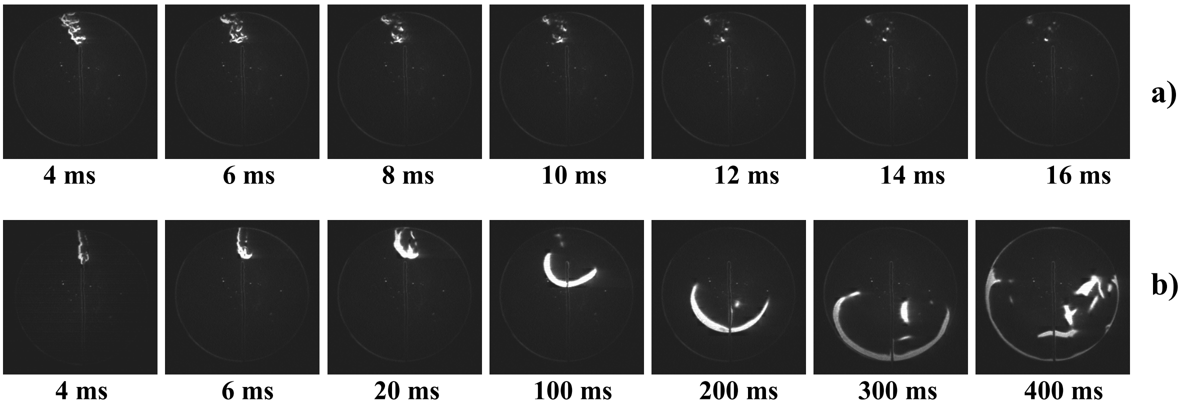

Figure 3. Schlieren snapshots of ignition by spark plug (a) and corona (b). CH_4/Air mixture of equivalence ratio 0.517. Time "0" corresponds to the beginning of discharge.

The advantage of corona ignition over spark plug ignition becomes apparent more clearly in the tests when a CH_4/air mixture of equivalence ratio 0.517 has been used. It is worth noting that spark plug ignition doesn't allow combustion in the whole volume of the combustion chamber. As can be seen in Fig. 3a, in this regime, ignition occurs only in the spark gap and then the flame is quenched. The use of a corona discharge of 3 ms duration allows the ignition of this extremely lean fuel mixture and flame propagation through the combustion chamber (Fig. 3b). In tests with a CH_4/air mixture of equivalence ratio 0.517, the discharge energy is 16.4 mJ and 0.63 mJ for spark and corona (with igniting streamer), respectively.

Conclusion

Comparison of spark plug and corona abilities to ignite lean fuel mixtures shows that corona discharge allows more efficient ignition with much less discharge energy. In extremely lean fuel mixtures, the corona allows the regime of ignition and flame propagation. This regime can't be realized using a more powerful spark discharge. A pulse corona also provides faster combustion due to generation of intensive turbulent flow around the discharge electrodes.

References

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