Spark Ignition in the Pre-Heated CH_4-Air Mixtures Behind Reflected Shock Waves

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Spark ignition of premixed CH_4-Air mixture was investigated using shock tube technique. For preliminary gas compression and heating the reflected shock wave was used. Spark breakdown was initiated after the shock wave reflection. Standard IC engine spark plug with discharge gap of 2 mm was used. System of spark initiation allows gas discharge parameters adjustment within the following ranges: discharge current from 25 to 400 mA; discharge time from 10 μs to 10 ms; total energy of the discharge from 1 to 300 mJ.

Flame propagation was investigated using flame self-emission technique and high-speed laser-schlieren photography.

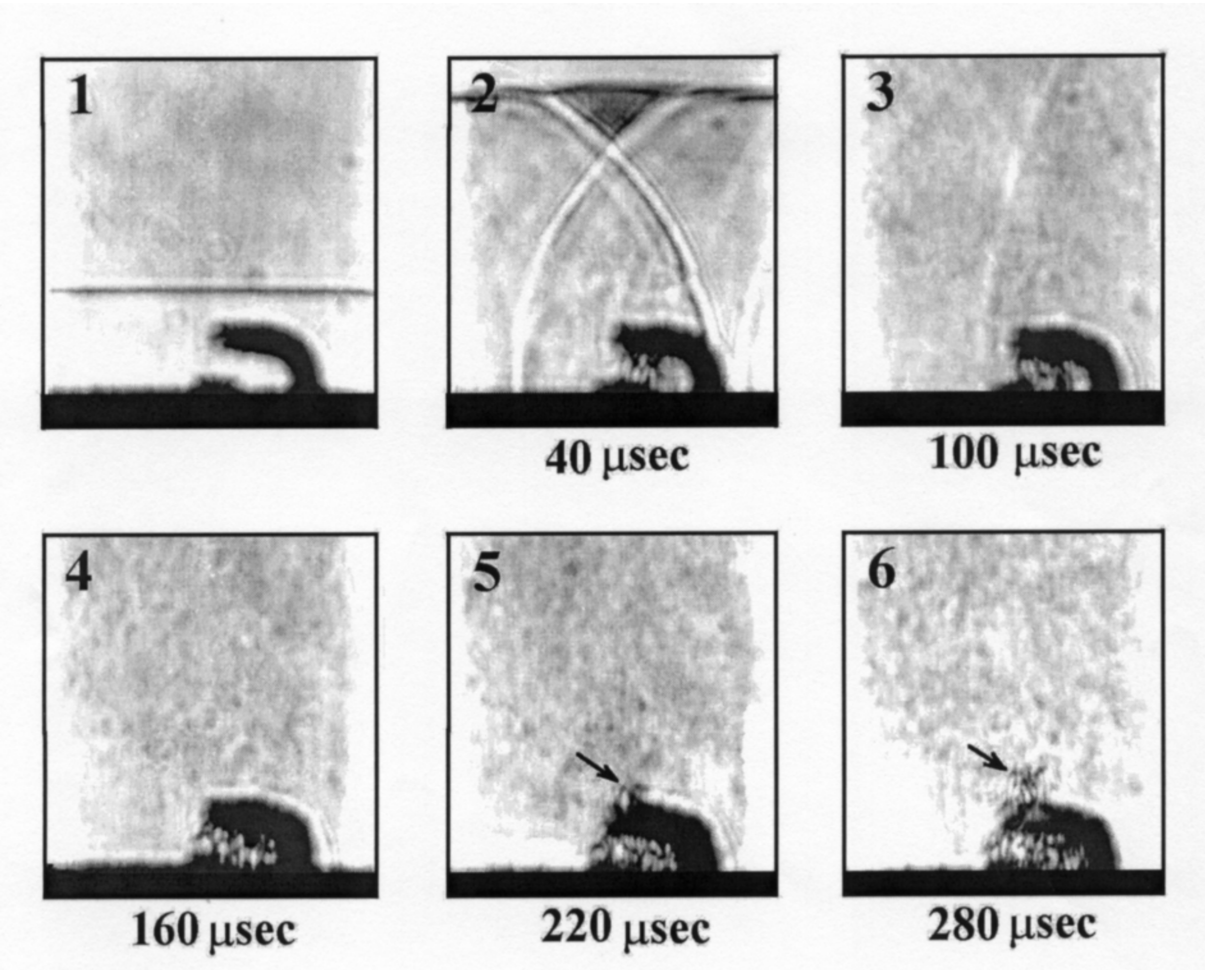

Figure 1: Spark discharge ignition initiation and flame propagation behind reflected shock wave. $T_5 = 480$ K, $P_5 = 4.5$ atm, mixture 9.4% CH_4-Air

Figure 1 shows the series of shlieren photos for spark discharge ignition initiation and flame propagation behind reflected shock wave in methane-air stoichiometric mixture. Initial gas parameters are: temperature $T_5 = 480$ K, pressure $P_5 = 4.5$ atm. This series allows to trace the dynamics of flame front formation in such a conditions. Incident shock wave arises in the second frame. The third frame demonstrates the reflected shock wave front with secondary discontinuities behind it. The secondary discontinuities form during the spark channel expansion and then propagate through the gas region behind the reflected shock. In the subsequent frames flame front becomes symmetrical with respect to the shock tube axis. Stable cylindrical flame front propagates along the shock tube channel until it's length becomes comparable with the channel diameter. After that cylindrical flame front becomes unstable and changes the shape to the quasi-spherical one. When the transverse size of the flame front reaches the diameter of the shock tube channel, the heat exchange rate increases, and the velocity of flame front propagation decreases.

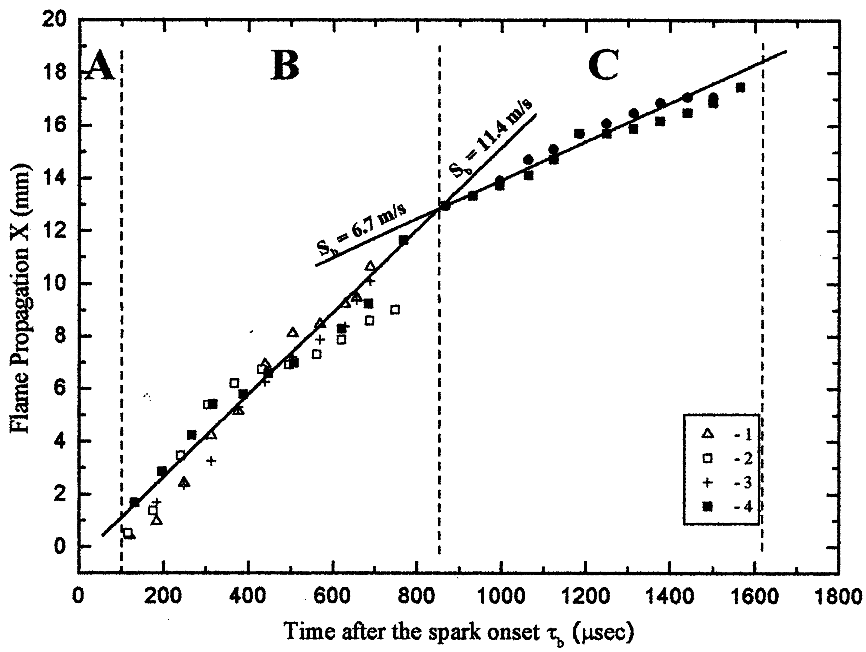

Figure 2: $x - t$ diagram of the flame front propagation in stoichiometric methane-air mixture. $T_5 = 480$ K, $P_5 = 4.5$ atm. 1,2 - Breakdown initiation; 3 - arc, 400 mA, 2.0 ms, 4 - arc, 400 mA, 0.5 ms.

In figure 2 $x-t$ diagram of the flame front propagation is represented for stoichiometric methane-air mixture and different regimes of ignition. Non-stationary character of the flame propagation is clearly seen. Flame appearance outside the anode corresponds to the time 120-150 μs after the discharge initiation (Region A). During the mentioned time (so called delay time of flame front propagation) the flame initiates inside the interelectrode gap. In the region adjacent to the anode (it is 13 mm in length and corresponds to the region B in the figure) the average velocity of the flame propagation is practically constant and equal to $S_B = 11.4$ m/s. Further flame front slows down (region C) due to development of front instabilities. It is clearly seen from the photographs that mentioned effect is connected with appearance of mushroom-shaped structure (see frames 14-20). Flame front velocity in the region C is equal $S_C = 6.7$ m/s. More careful consideration of region B proves non-stationary character of the flame propagation. Really, initial velocity of the flame propagation (at $x < 7$ mm) is equal 19 m/s and doubles at the time moment about of 400 μs. This is in a good correlation with a structure given by frames 6-16. Till the cylindrical flame shape is observed (frames 6-9) flame front velocity is constant, but appearance of the mushroom-shaped structure leads to the flame deceleration. This feature clearly demonstrated by behavior of volume velocity of combustion (figure 3).

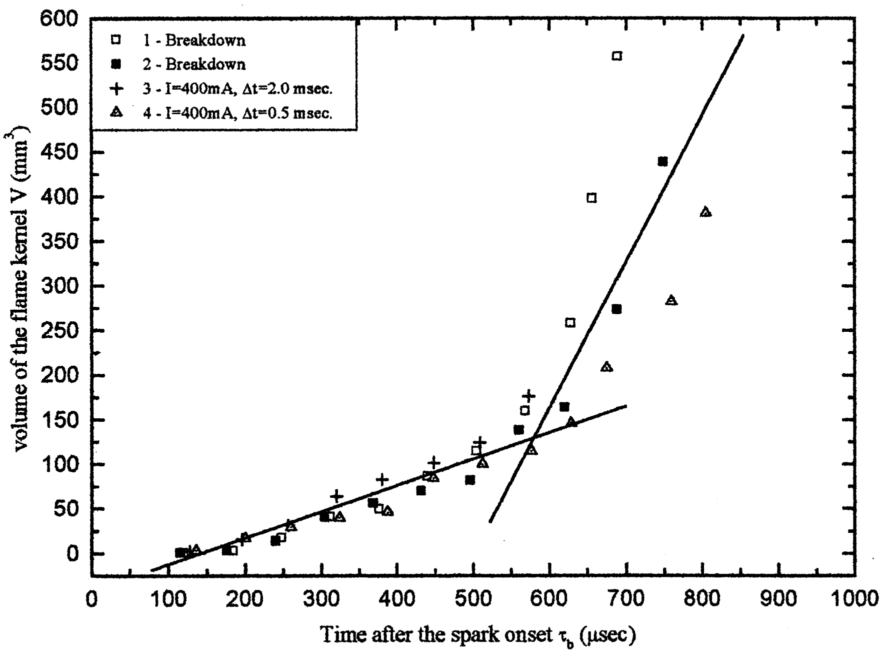

Figure 3: Volume velocity of combustion in stoichiometric methane-air mixture. $T_5 = 480$ K, $P_5 = 4.5$ atm. 1,2 - Breakdown initiation; 3 - arc, 400 mA, 2.0 ms, 4 - arc, 400 mA, 0.5 ms.

Volume velocity increases sharply at the time moment 550 μs, which corresponds to the 7 mm distance from the anode, at the point where mushroom-like structure appears. Thus, there are three characteristic regions in the flame front development behind the reflected shock wave: region A corresponds to the flame initiation inside the interelectrode gap; in the region B cylindrical- shape flame front develops; its velocity slows down with appearance of mushroom-shape structure, while volume velocity increases and front becomes to propagate in the radial direction. Final stage, C, corresponds to the spherical-shape flame propagation with relatively low velocity.

In the figure 4 the averaged trajectories of the flame front in the lean and stoichiometric methane-air mixtures at different ignition conditions are shown. On one hand, it is clearly seen that dynamics of the flame front propagation in the lean and stoichiometric mixtures differ from each other and velocity of the flame front propagation is greater in stoichiometric mixture. On the other hand, the difference between different regimes of

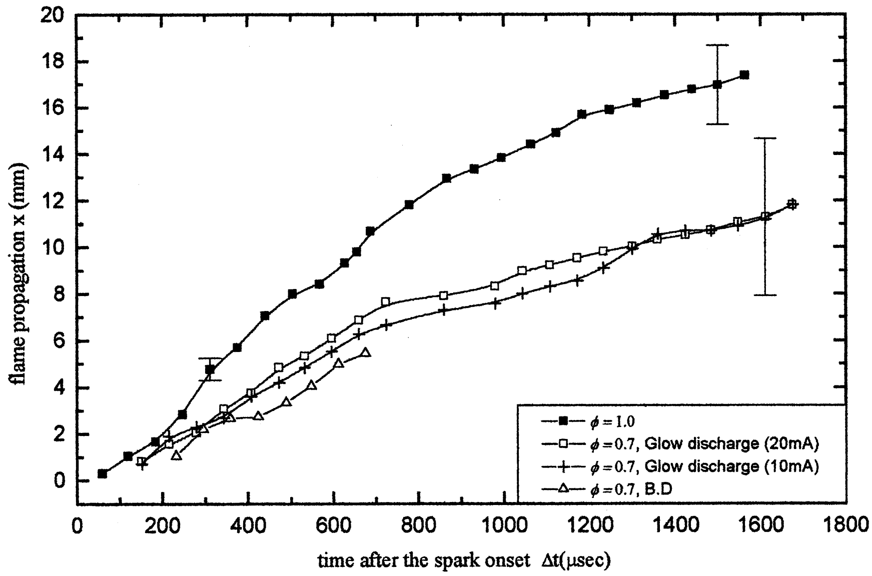

Figure 4: Averaged trajectories of the flame front in Methane-Air mixtures. $T_5 = 480$ K, $P_5 = 4.5$ atm.

the ignition initiation is practically absent. It means that the main energy release into the gas takes place during the gap breakdown and the glow discharge stage plays the negligible role in the process of ignition initiation. The effect of the characteristic time of the discharge appears in the case of the intensive gas motion through the gap. In this case the arc channel treats the large gas volume and intensifies the ignition process.

It is possible to underline the general peculiarities of the flame propagation (figure 4):

- On the initial part of the trajectory the flame velocity greater than on the final one for all cases which was connected with the heat exchange regime modification;

- Variation of the ignition initiation regime practically does not change the flame front propagation regime.

The peculiarities mentioned are clearly seen from the analysis of flame front velocity represented in figure 5. It is seen from the figure that flame front velocity in the lean mixture decreases sharply at $t = 700$ μs after ignition and tends to laminar velocity of combustion for the given conditions, $S_{b(f=0.7)} = 1.35$ m/s. Dynamics of the velocity differs from the previous case. Front deceleration period is significantly longer (1200 μs) and tends to the laminar limit equal to $S_{b(f=1.0)} = 3.5$ m/s.

The numerical 3D-modeling of flow field near the shock tube end plate was performed in the CH_4-air stoichiometric mixture N_2:O_2:CH_4= 0.714 : 0.190 : 0.096. Grid dimension was $150 \times 75 \times 75$, cell size $dx = dy = dz = 0.2$ mm. Initial gas parameters were: shock wave velocity $U_s = 532$ m/s, $p_1 = 760$ Torr.

Spark was modeled as an instantaneous energy release in the spark gap with temperature increase up to $T_{spark} = 6000$ K and corresponding pressure growth. Spark arises exactly at the time moment when incident shock wave reaches the shock tube end plate.

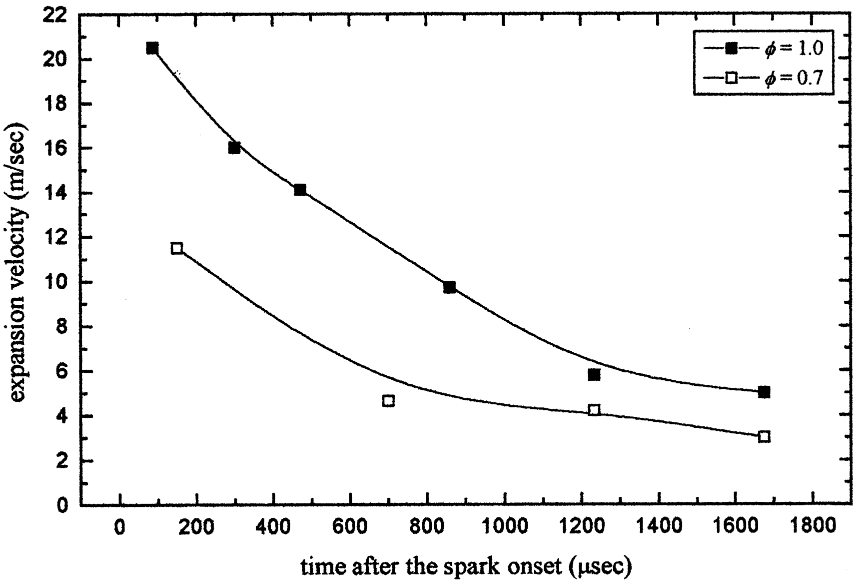

Figure 5: The flame velocity dynamics for lean and stoichiometric Methane-Air mixtures. $T_5 = 480$ K, $P_5 = 4.5$ atm.

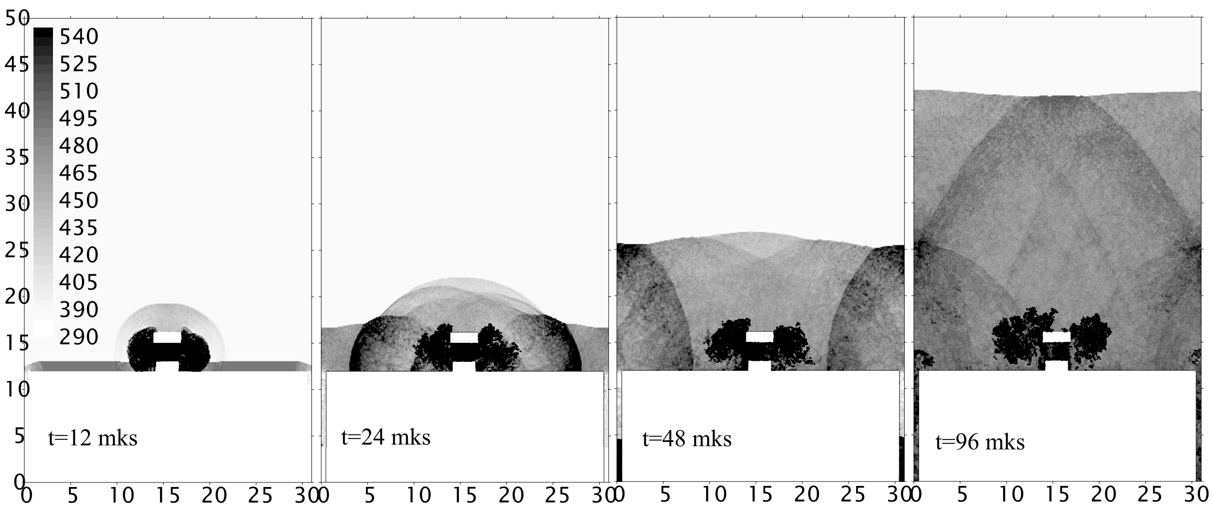

Figure 6: The temperature field dynamics for stoichiometric Methane-Air mixtures. Shock wave velocity $U_s = 532$ m/s, $p_1 = 760$ Torr. Distance, mm.

It is clearly seen the hot gas propagation around the low-voltage electrode of the spark plug (Fig.6).

Radial blast wave from the spark reaches the wall of the shock tube. Subsequent shock wave focusing near the tube center leads to the local temperature growth and hot channel formation near the center. Ignition of the mixture arises in this region and forms a narrow burned zone. Thus, formation of the first "cylindrical" flame kernel in the experiments may be explained by the temperature field nonuniformity in the vicinity of the spark plug.