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FLAME FRONT SPATIAL CONFIGURATION AT DEFLAGRATION TO DETONATION TRANSITIONS IN DILUTED STOICHIOMETRIC ACETYLENE-OXYGEN MIXTURES

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Main subjects: deflagration to detonation transition
Fluid: reaction flow
Visualization method(s): pressure and ion-current sensors signals analysis, high speed video recording
Other keywords: spatial configuration of accelerating flame, hot spot, acetylene-oxygen mixtures

ABSTRACT: *Significant impact on the formation and characteristics of the detonation wave has the gas turbulence and a flame acceleration following the leading shock wave in the gas. We combined traditional techniques (pressure and ion-current sensors) and high-speed video recording to study the deflagration to detonation transition (DDT) in diluted stoichiometric acetylene-oxygen mixture at low energy ignition mode in smooth-walled cylindrical tube. As the result the quantitative data on dynamics of the shock wave and the local flame velocities, the spatial behavior of the flame during its acceleration, the length of flame front and the distance between the shock wave and the flame front were determined. The appearance of hot spots before the onset of detonation was recorded and their spatial positions relative to the wall of the tube and the accelerating flame front were determined.*

Introduction

The studies of detonation have been conducted for many years. There is a lot of material on this topic. However, due to the lack of a complete theory that can accurately predict the formation of detonation wave and its behavior at certain conditions and because of the attempts to use the detonation in energetic and engines, the experimental studies of the deflagration to detonation transition (DDT) are still actually.

It is known from the experimental studies that significant impact on the DDT has the gas turbulence and a flame acceleration behind the leading shock wave in the gas [1, 2]. Visualizations of DDT using schlieren techniques allowed seeing how the detonation wave appears from the hot spots [3, 4]. Most experiments on schlieren visualizations of DDT were performed in square tubes and powerful spark gap or high-pressure driver mixtures were used. Such initiation tools resulted usually in formation of relatively strong leading shock wave and enhanced gas parameters in post-shock flow, which could affect strongly on subsequent DDT scenarios. However, for practical applications the study of behavior of accelerating flame and hot spot appearance before the detonation onset in cylindrical tubes at low energy ignition is more interesting.

In this work, we combined traditional techniques (pressure and ion-current sensors) and high-speed video recording of self-luminescence to study the DDT in a stoichiometric acetylene-oxygen mixture with argon and nitrogen dilution at low energy ignition mode. As the result the quantitative data on dynamics of the shock wave and the local flame velocities, the spatial behavior of the flame during its acceleration, the length of flame front and the distance between the shock wave and the flame front

were determined. The appearance of hot spots was recorded and their spatial positions in the tube relative to the flame front were determined.

Experimental

The experiments were performed in cylindrical stainless steel tube with inner diameter (d) of 0.04 m and total length of 5.55 m (Fig. 1). The calibrated smooth-walled tube was used to minimize the influence of wall roughness on the gas turbulence and flame acceleration. The ratio of the length of the tube to its diameter was near 140 to prevent the influence of compression wave's reflection from the back end of the tube on observing DDT scenarios. The combustion was initiated at the front end of the tube by the standard automobile spark plug. The ignition point was located on the axis of the tube. To ensure the low energy ignition mode the ignition energy was about 0.8 mJ.

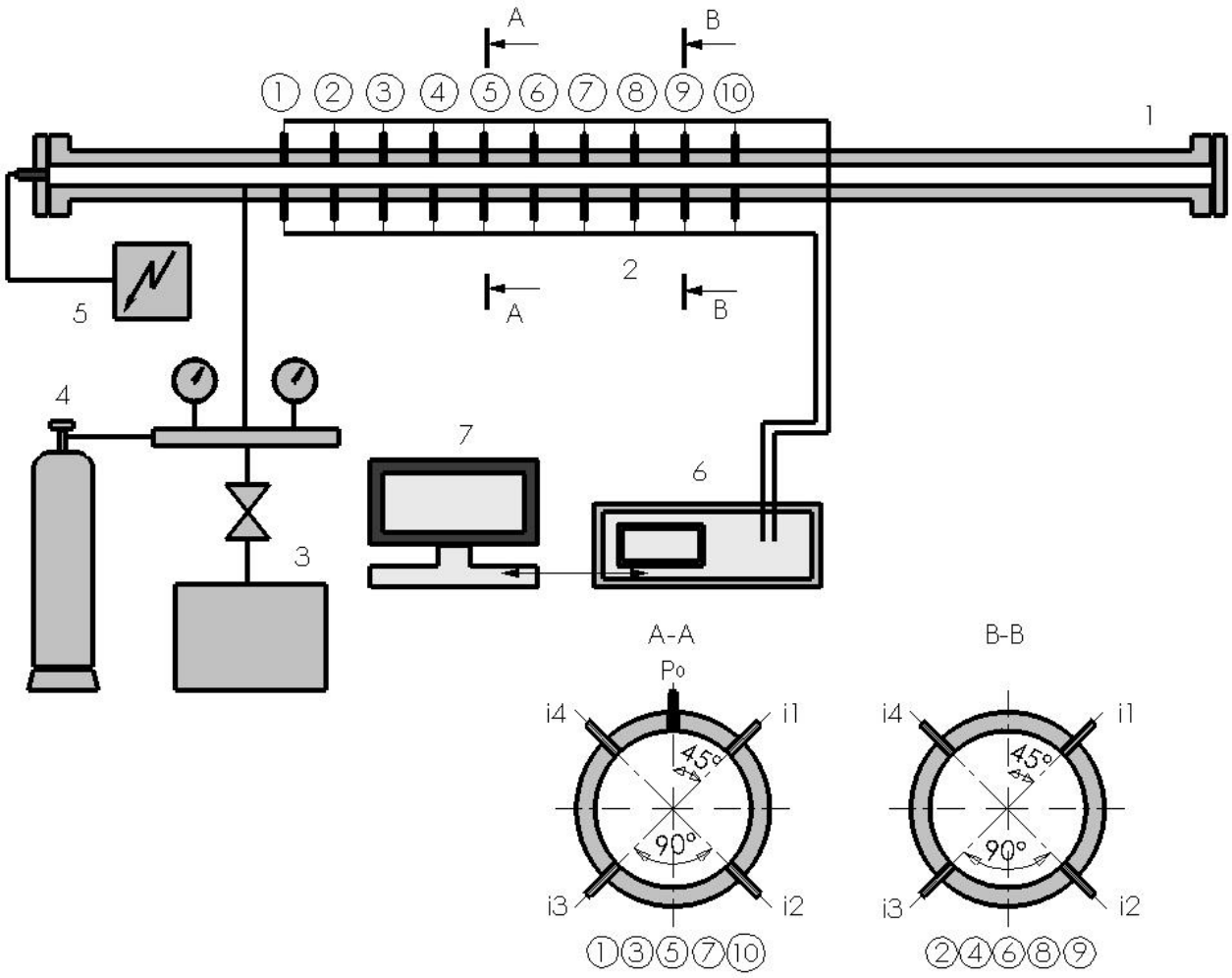


Fig. 1. Experimental setup:
1 – stainless steel tube; 2 – test section; 3 – vacuum pump; 4 – test gas; 5 – ignition unit; 6 – digital oscilloscopes; 7 – PC

The test section was located at distance 2.77 m from the ignition point. It consist of 10 measuring cross-sections with the distance of 0.06 m between them. The measuring cross-sections of the tube

were arranged as it is presented in Fig. 1. Each measuring cross-section was consisted of four ion-current sensors and additionally five cross-sections (1, 3, 5, 7 and 10 in Fig. 1) had high frequency pressure sensor. Ion-current sensors with the same angular position relative to the axis of the tube were integrated into four measuring lines. Thus, the local velocities of flame and shock wave in near wall region, the spatial behavior of flame, the length of flame front and the distance between the shock wave and the flame front had been carefully studied over the length of 0.54m.

High-speed video observations of self-luminescence at DDT were carried out in the transparent smooth-walled cylindrical plastic tube with inner diameter of 0.04 m and total length of 6.07 m. The maximum frame rate of the camera was 200 000 fps and the minimum exposure time was 1 μs.

Stoichiometric acetylene-oxygen mixtures with 70 % of argon dilution (8.6% C_2H_2 + 21.4% O_2 + 70% Ar) and with 60 % of nitrogen dilution (11.4% C_2H_2 + 28.6% O_2 + 60% N_2) were used as the test gases. They were prepared by the method of partial pressures. The initial pressure in experiments was 20.0 – 50.0 kPa and 13.6 – 50.0 kPa for mixture with Ar and N_2 dilution respectively. The initial pressure of test mixture was chosen in a way to register the pre-detonation combustion, the deflagration to detonation transition or the detonation wave in the test section of the tube.

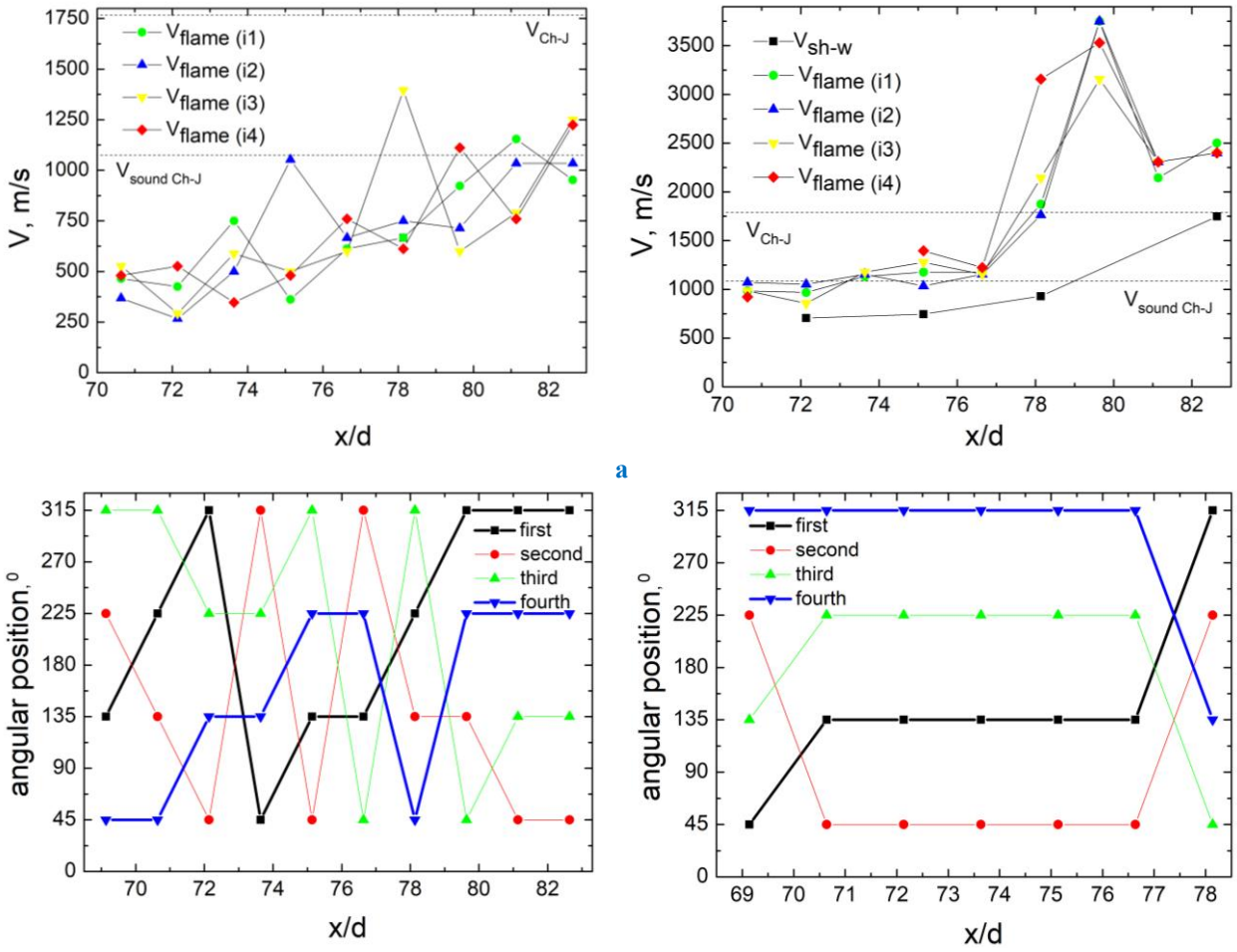
It was planned to study stoichiometric acetylene-oxygen mixtures with 70 % of nitrogen dilution. However, experiments showed that for this mixture it was impossible to register the DDT in test section. The only slowly deflagration wave or stationary detonation wave were registered. Reducing the degree of nitrogen dilution to 60% allowed fixing the conditions for the study of the pre-detonation combustion and DDT in test section.

Results

Experiments in stainless steel tube showed that for studied mixtures with Ar and N_2 dilution acceleration of flame and DDT occurred in a similar way. We registered the propagation of the accelerating flame along the tube. The compression waves of low-intensity generated by the flame front were detected in front of it. We found, that because of low energy ignition mode in our experiments, only the last pressure sensor before the onset of detonation indicates the formation of intensive leading shock wave. That is why it was impossible to obtain correct data on the velocity of leading shock wave in some experiments, especially for the case of pre-detonation combustion. Before the onset of detonation, flame front arrived to different ion-current probes situated in the same measuring cross-section at different times. Therefore, its shape was not plane and had complex extended spatial form. However, the extension of front decreased with its velocity increasing.

Typical experimental results for two combustion modes (pre-detonation and DDT) registered in the measuring section and obtained changes in the local velocities of flame front and its spatial configuration are shown in Fig. 2, 3.

Generally for both studied mixtures (with Ar and N_2 dilution), two typical stages of flame acceleration were registered in experiments. At flame velocities less than isobaric sound speed of detonation products, the spatial configuration of flame front was highly unstable and showed strong transverse vibrations in the direction perpendicular to the axis of the tube (left graphs in Fig. 2, 3). For these pre-detonation regimes, different regions of the flame front were changing their angular location continuously, but in some experiments, the rotation of the flame front (especially its leading and remote edge) along the tube axis as a single complex was registered. The average transverse components of the flame velocity was close to the velocity of the chocked flow behind the leading shock wave.



a

b

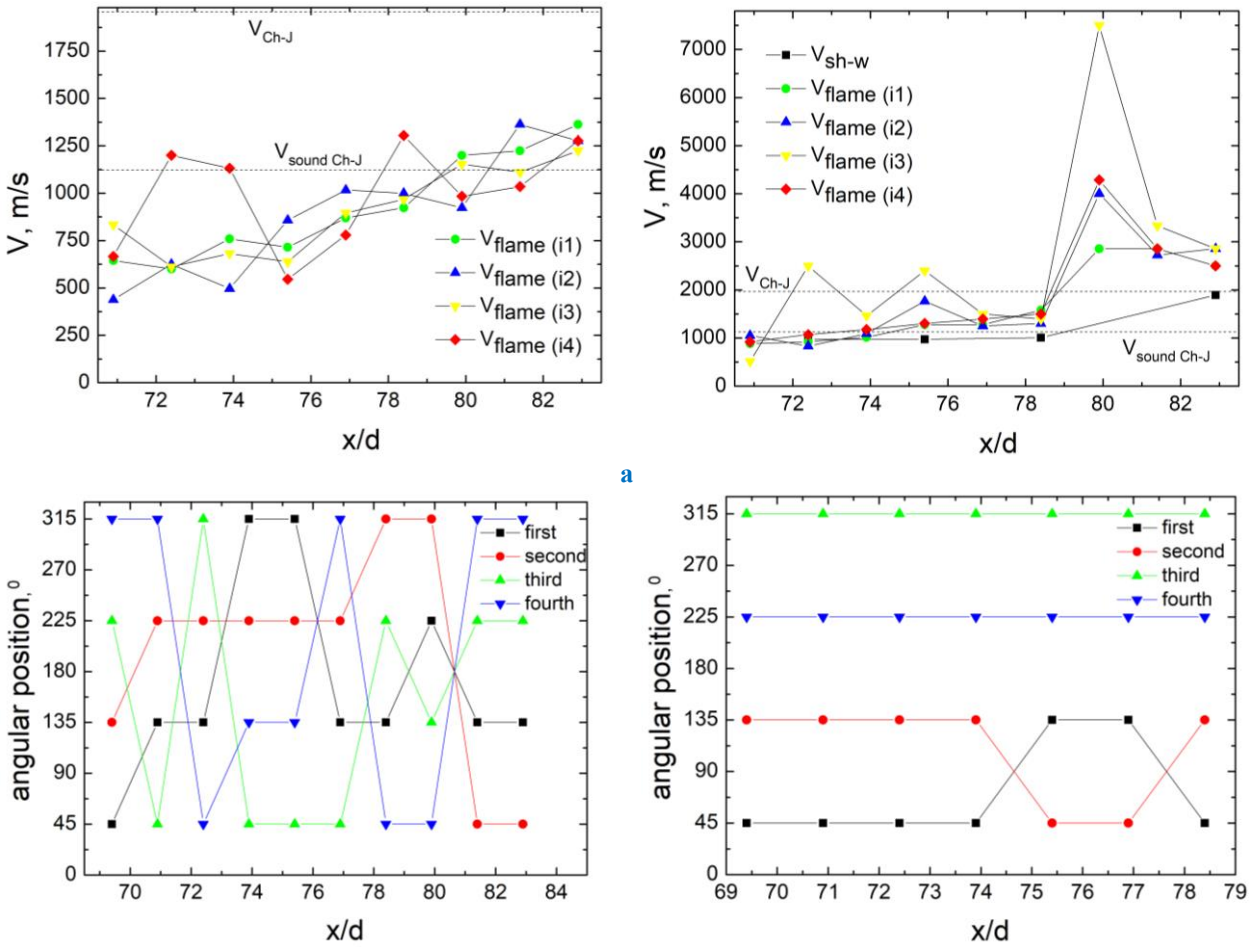
Fig. 2. DDT in 8.6% C_2H_2 + 21.4% O_2 + 70% Ar:
on left ¬ at 20 kPa (pre-detonation combustion); on right ¬ at 35 kPa (DDT);
a – ¬local velocities of the flame and shock wave, V_{Ch-J} and isobaric sound speed of detonation products;
b –¬ the order of local flame arrivals to the ion probes with different angular position at measuring cross-section

When the flame velocities have achieved the isobaric sound speed of detonation products, the spatial configuration of flame front became more stable (right graphs in Fig. 2, 3). In these regimes (close to the detonation onset), the flame front propagated along the tube as almost the stable complex with a fixed orientation. Such behavior of flame front was registered before the appearance of detonation wave.

Based on the data obtained, the length of the flame front along the tube (i.e. the distance between leading and remote edge of the flame) was calculated by multiplying the difference in arrival time between remote and leading edges of the flame by their mean velocity. Because we determined the arrival time of flame front near the wall of tube thus the real front length could be longer. At the beginning of the test section at pre-detonation mode, it was maximum and equaled to ~ 2d and ~ 4d for mixture with Ar and N_2 dilution respectively.

The distance between the leading shock wave and combustion front was calculated by multiplying the difference in arrival time between remote edge of the flame front and the shock wave by the velocity of the flame front. Its maximum values were ~ 10d and ~ 8.5d for mixture with Ar and N_2 respectively.

However, this distance decreased significantly with the flame acceleration along the tube and attained the minimal values of ~ 1.5d and ~ 1d for studied mixtures.

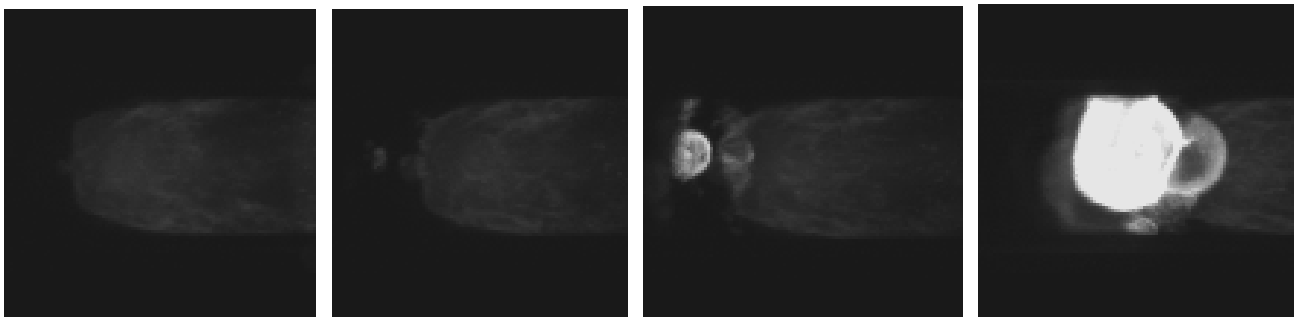


a

b

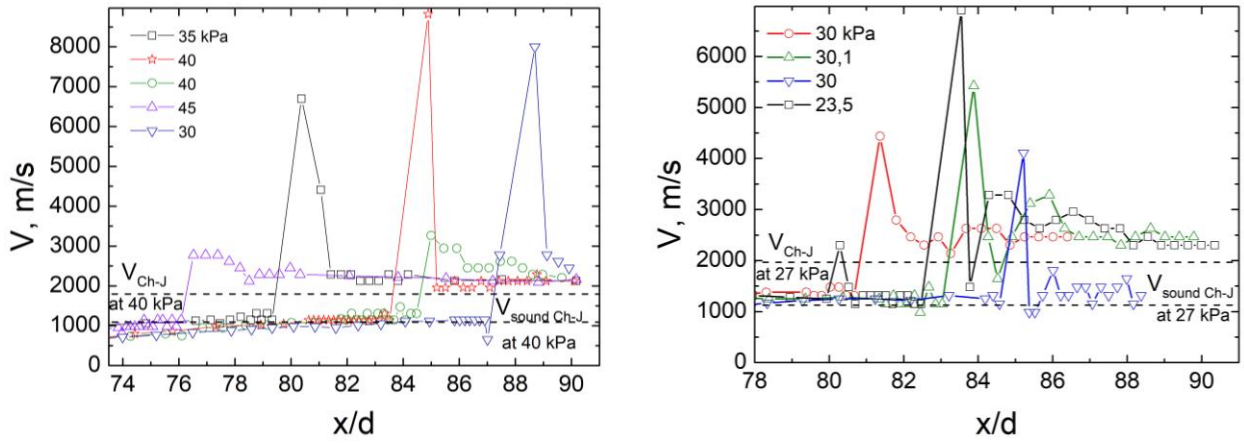
Fig. 3. DDT in 11.4% C_2H_2 + 28.6% O_2 + 60% N_2:
on left ¬ at 22 kPa (pre-detonation combustion); on right ¬ at 30 kPa (DDT);
a – ¬local velocities of the flame and shock wave, V_{Ch-J} and isobaric sound speed of detonation products;
b –¬ the order of local flame arrivals to the ion probes with different angular position at measuring cross-section

High-speed video observations of self-luminescence at DDT in studied mixtures with Ar and N_2 dilution were carried out in the transparent smooth-walled cylindrical plastic tube. The propagation of accelerating flame before the onset of detonation was observed. In most cases, the observed flame front was extended along the tube axis, and its extension decreased with velocity increasing. The length of flame front was obtained from the frames analysis. Its maximum and minimum values were ~ 2d and ~ 0.5d, and ~ 4d and ~ 0.5d for mixtures diluted with Ar and N_2 respectively. These data in good agreements with calculated lengths of flame front obtained on the base of ion-current measurements. When the velocity of flame had reached a certain value, a hot spot appeared ahead of it, local explosion of the mixture and formation of the detonation wave occurred. An example of video observations and typical reconstructed velocities of flame front in different experiments are shown in the Fig. 4 and Fig. 5 respectively. Obtained data show that hot spots formation took place when the flame velocity begins to exceed the isobaric sound speed of detonation products (Fig. 5).



28.21250 ms 28.23125 28.23750 28.24375

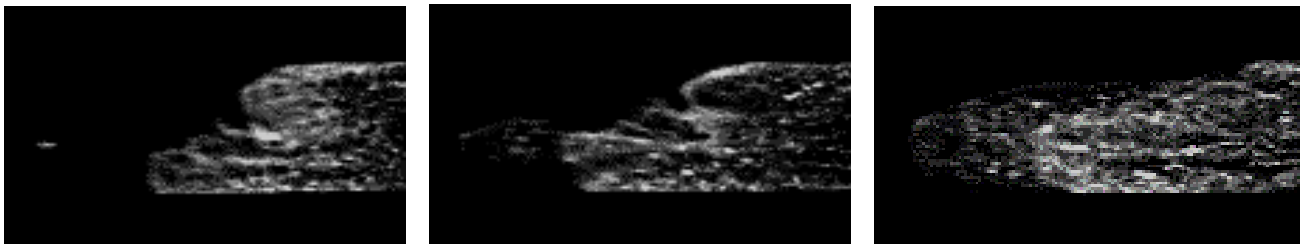
Fig. 4. High-speed video observation at DDT in 11.4% C_2H_2 + 28.6% O_2 + 60% N_2 at 14 kPa



a b

Fig. 5. Observed velocities of flame at DDT in a 8.6% C2H2 + 21.4% O2 + 70% Ar (a) and 11.4% C2H2 + 28.6% O2 + 60% N2 (b)

The onset of detonation from a hot spot in mixtures with Ar and N_2 dilution was different. Usually one or several hot spots appeared in front of flame in mixture with dilution of N_2, but in some experiments detonation did not expand from them. The new combustion wave propagated from the hot spot and joined with the initial flame (Fig. 6, black and blue curves in Fig. 5b). This happened until the detonation appeared from the new hot spot. In some experiments, the appearance of hot spots in front of flame without onset of detonation was observed at the distance ~ 1 m.



29.37500 ms 29.44375 29.54375

Fig. 6. High-speed video observation at DDT in 11.4% C_2H_2 + 28.6% O_2 + 60% N_2 at 13.6 kPa

Frequently several hot spots appeared simultaneously in front of flame in mixture with dilution of Ar, and the local explosion with further formation of the detonation wave emerged almost immediately from one of them or simultaneously from several. In some experiments appearance of hot spots was

observed in the volume of burning gas, but was determined that hot spot appeared in the volume of unburned gas, which could be hidden by the burning gas.
The locations of the hot spots relative to the leading edge of the flame front and the walls of the tube for both studied mixtures were analyzed. The maximum distance along the tube between hot spot and the leading front of flame was ~ 0.9d and ~ 1d for mixtures diluted with Ar and N_2 respectively. After analyzing obtained data, we concluded that the formation of hot spot occurred in the near-wall region of the tube (as it was shown by Soloukhin [5]).
Our results indicate the appearance of hot spot and subsequent DDT in the boundary layer between the leading shock wave and flame front. They are in good agreements with the theoretical and experimental studies [6, 7] noted the importance of the formation of the boundary layer on the DDT. Initial shock wave produces the boundary layer. The following shocks generated by the flame front interact with it and heat to the temperature at which the auto-ignition (hot spot) occurs. Therefore the new wave of flame appears or local explosion occurred and detonation wave appeared.

Conclusion

Experimental studies of DDT in 8.6% C_2H_2 + 21.4% O_2 + 70% Ar and 11.4% C_2H_2 + 28.6% O2 + 60% N_2 mixtures were carried out in the smooth-walled cylindrical tube. The spatial configuration of the flame during acceleration was investigated, and local velocities of the flame and shock wave at DDT were detected.
The maximum length of flame front along the tube was obtained from local ion-current measurements. It was ~ 2d and ~ 4d for the mixture with Ar and N_2 dilution respectively. The maximum distance between the leading shock wave and the flame front was ~ 10d and ~ 8.5d for mixture with Ar and N_2 respectively. This parameter decreased with the flame acceleration and attained the minimal values of ~ 1.5d and ~ 1d for studied mixtures.
Was registered that at the flame velocities less than isobaric sound speed of detonation products, the spatial configuration of the flame front was highly unstable with strong transverse vibrations. But with velocity increasing to the isobaric sound speed of detonation products, the behavior of the flame front became more stable.
High-speed video observations of self-luminescence at DDT were carried out in the transparent smooth-walled cylindrical plastic tube. At the velocity of flame near the isobaric sound speed of detonation products hot spot appeared near the wall of the tube between the leading shock wave and flame front. The maximum distance between hot spot and leading flame front was ~ 0.9d and ~ 1d for mixtures diluted with Ar and N_2 respectively. The detonation wave expanded from this hot spot.

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