Hot spots formation at DDT in cylindrical tube

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1 Introduction

There is still no complete theory that can clear describe the observed experimental data on deflagration to detonation transitions (DDT) in gases and accurately predict its behavior at certain conditions. That is why experimental studies of DDT are still actually. Furthermore, DDT is very complex and unsteady phenomenon, which is sensitive to local interplay between gasdynamics and chemical reactions at different flow and boundary conditions.

The study of hot spot occurrence and distance of induction zone at deflagration to detonation transition (DDT) in gases is important fundamental and practical problem. Understanding and accurate description of this complex gasdynamics and chemical reactions process can help to predict onset of detonation in specific conditions and it application in detonation propulsion systems [1].

This work is a continuation of our experimental study of DDT in smooth-walled cylindrical tube at low energy ignition mode (0.8 mJ) [2]. We carried out high speed video observations of self-luminescence at DDT in stoichiometric C_2H_2–O_2 mixture with Ar and N_2 dilution and induction time study in shock tube for close initial conditions. This allowed us to estimate the observed local temperature for hot spots formation at DDT in studied mixtures and compare it with ideal values calculated for experimental post-shock conditions.

2 Experimental setup

High-speed video observations of self-luminescence at DDT were carried out through the transparent smooth-walled cylindrical plastic tube with inner diameter (d) of 0.04 m and total length of 6.07 m (Figure 1). The ratio of the length of the tube to its diameter was near 150 to prevent the influence of compression wave's reflection from the end wall on observing DDT scenarios. The test gas was ignited at the front end of the detonation tube by the standard 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.

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The axis of the high-speed video camera was located perpendicular to the tube axis at the same level. The distance between camera and plastic tube was 1 m, so the observation length was 1.02 m. The maximum frame rate of the camera was 200 000 fps and the minimum exposure 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. The test mixtures were prepared by the method of partial pressures.

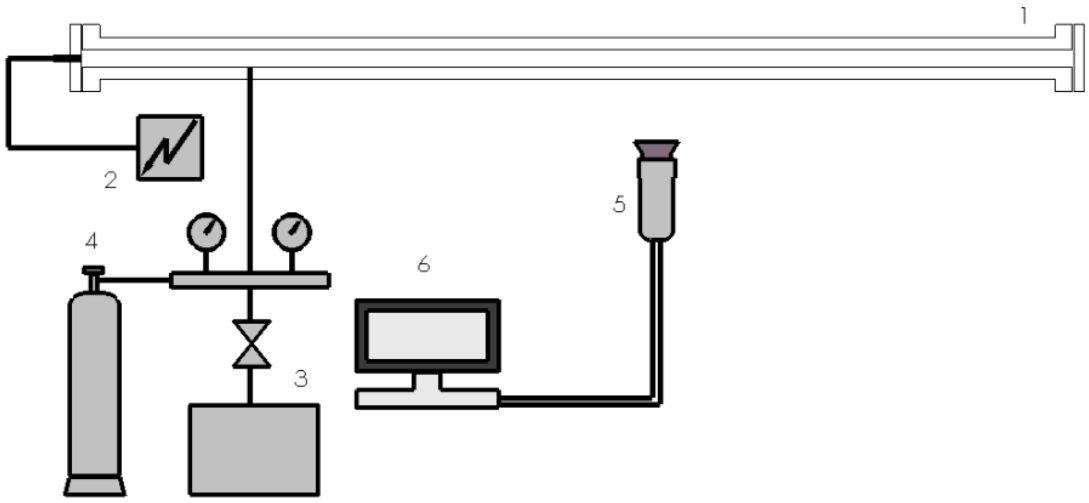


Figure 1. Experimental setup: 1 – transparent smooth-walled cylindrical plastic tube; 2 – ignition unit; 3 – vacuum pump; 4 – test gas; 5 – high-speed video camera; 6 – PC

The auto-ignition measurements were carried out in shock tube with inner diameter of 0.05 m and a length of 8.5 m behind reflected shock wave at conditions equivalent to post-shock flow parameters before DDT events in plastic tube. A detailed description of the experimental setup was presented in [3]. Measurements of the ignition delay time were performed by registration of photoluminescence of the CH radical transition ($^2\Delta$ -$^2\Pi$) at a wavelength of λ = 431.5 nm along the axis of the shock tube. For filtering desired wavelength emission the narrowband filters λ_{max} = 430.8 nm, $\Delta\lambda_{0.5}$ = 2.6 nm were used. Additionally, the C_2 molecules emission were registered in the boundary layer at a wavelength of λ = 516.5 nm using a filter λ_{max} = 516.3 nm, $\Delta\lambda_{0.5}$ = 4.6 nm. Induction time was defined as the time between the arrival of the incident shock wave at the end wall of the shock tube and the beginning of the emission at selected wavelengths or the beginning of the pressure increase.

3 Results and discussion

High-speed video recordings of self-luminescence at DDT allowed noting the main peculiarities of the process in studied mixtures. They allow also reconstructing the dynamic of observed flame velocity in experiments. An example of obtained video records is shown in the Figure 2.

It was evident from the videos, that gas flow in front of the flame was highly turbulent. In most cases the observed flame front was extended along the tube axis. The flame extension was measured from the image analysis. Its maximum and minimum (before the onset of detonation) values were 0.085 m (~ 2d) and 0.018 m (~ 0.5d), and 0.148 m (~ 4d) and 0.018 m (~ 0.5d) for mixtures diluted with Ar and N_2, respectively.

When the flame velocity had attained a certain critical value, a hot spot appeared ahead of it, and local ignition with subsequent explosion of the mixture was observed in compressed slug of unburnt mixture ahead of the flame (Figure 2). Our observations showed that hot spots formation took place when the flame velocity begins to exceed the isobaric sound speed of combustion products. This result in agreement with our data obtained in [2].

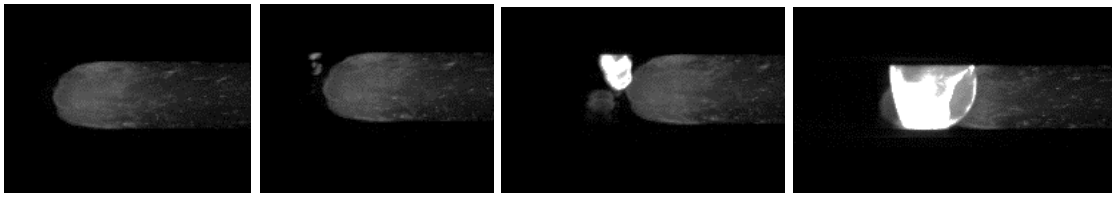


Figure 2. High-speed video registration of self-luminescence at DDT in 11.4% C_2H_2 + 28.6% O_2 + 60% N_2 at 14 kPa

The scenario of detonation onset from forming hot spots in mixtures with Ar and N_2 dilution was slightly different. Usually one hot spot appeared in front of the flame in mixture with dilution of N_2. The new reaction front propagated from the hot spot and combined with the main flame. This happened until the detonation appeared from the new hot spot. In some experiments the periodical appearance of hot spots in front of the flame without onset of detonation was observed at the travelling distance of ~ 1 m. This re-ignition scenario can be compared with weak ignition mode observed for different fuels in shock tube experiments behind reflected shock waves [4]. In other cases depending from initial pressures usually the transient ignition modes [3] were detected when one or several expanding reaction fronts propagated from re-ignited hot spots. They produced an addition compression of unburnt mixture ahead of the flame, which resulted in subsequent detonation formation. So, generally speaking, it looks like deflagration to detonation transitions in a slug of compressed flow ahead of accelerating flame.

For both studied mixtures, the spatial disposition of hot spots (relative to the leading edge of the flame and leading shock wave [2]) in the plane of visualization is shown in Figure 3. General statistic shows that for N_2 diluted mixture in 95.5% of experiments a new hot spot occurred ahead of the leading tip of the flame. Only in two experiments (4.5% of events) new hot spots were observed in some location close to cross-section of the leading tip of the flame.

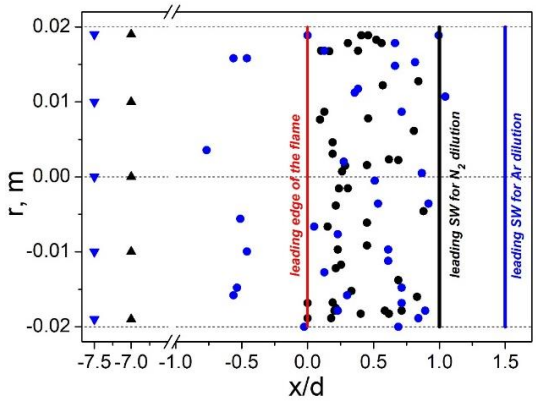
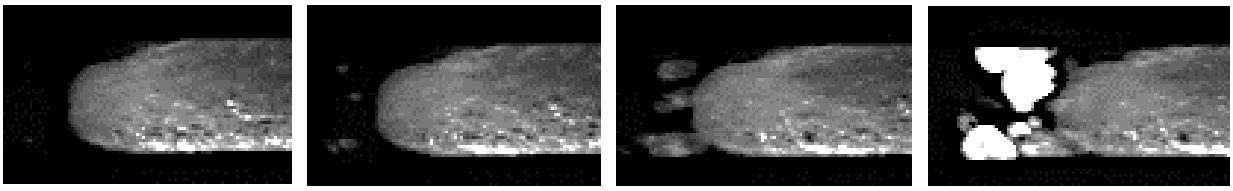


Figure 3. Hot spots (points) spatial disposition relative to the leading shock wave and flame and, evaluated on the basis of ignition delay time measurements induction zone lengths (triangles) in mixtures diluted with Ar (blue) and N_2 (black)

For Ar diluted mixture because of the higher specific heat capacity and, consequently, stronger compression of unburnt slug of the mixture at the same heat release, several hot spots ignition appeared simultaneously in several locations ahead of the flame, and subsequent local transitions to detonation occur quickly from one or from several locations (Figure 4). In 20% of experiments, hot spots formation was observed behind the leading tip of the flame in the volume of unburned gas, which could be hidden by the burning gas. Statistic shows (Figure 3) that for 80% of events a new hot spot occurred ahead of the leading tip of the flame.



20.21250 ms 20.21875 20.23125 20.23750

Figure 4. Multi hot spot ignition at DDT in 8.6% C_2H_2 + 21.4% O_2 + 70% Ar at 36 kPa

Analysis of video records indicates (Figure 3) that the maximum distance along the tube between hot spot and the leading tip of the flame was 0.042 m (~ 1d) and 0.035 m (~ 0.9d) for mixtures diluted with Ar and N_2 respectively. On many pictures in different experiments, it was evident that the formation of hot spot occurred in the vicinity of the tube wall (as it was shown by Soloukhin [5]).

Presented results (together with our results from [2]) indicate the appearance of hot spots and subsequent DDT occurs near the tube wall between the leading shock wave and flame front. This from one side is in agreements with the theoretical and experimental studies [6, 7, 8] noted the importance of the formation of the boundary layer on the DDT. Initial shock wave produces the boundary layer. The following compression generated by the flame front interact with it and heat to the temperature at which the auto-ignition (hot spot) occurs. Therefore the new flame appears. For sensitive mixtures appearance of hot spot leads to the immediate detonation onset. From other side our measurements [2] shows that at final stage of the flame acceleration the mean distance between leading shock wave and leading tip of the flame is ~ 1.5d and ~ 1d (Figure 3) for mixtures diluted with Ar and N_2, respectively. But a lot of hot spots in N_2 diluted mixture were formed close to shock wave plane. At such short distances the formation of developed boundary layer is hardly possible. One can say that only transition from laminar to turbulent boundary layer can be observed at such length scales. Thus, probably, another scenario has to be considered for explaining mechanism of hot spot formation.

Because we have carefully measured the local dynamics of heading shock wave and flame it was possible to evaluate ideal and real ignition delay (induction) times corresponding to local post-shock flow parameters required for hot spots formation. For this purpose, the auto-ignition and induction times of the studied mixture were measured in the shock tube behind reflected shock waves at post-shock conditions equivalent to mean temperature and pressure of the flow behind heading shock wave of accelerating deflagration.

Our measurements demonstrate that the minimum induction time at post-shock temperature ~ 860 K (corresponds to experimental conditions behind heading shock wave of accelerating deflagration) should be not less than ~ 1.35 ms and ~ 1.25 ms (yellow zone in Figure 5) for mixtures diluted with Ar and N2 respectively. In this ideal case, the corresponding minimum induction zone length should be ~ 9d and ~ 8d respectively. So, for such post-shock conditions hot spots can occur far behind the leading and remote edges of the flame in the flow zone occupied by reaction products (triangles in Figure 3).

The observed induction zone length is in the range of 0.45d – 2.27d and 0.12d – 1.00d (Figure 3) for mixtures diluted with Ar and N_2 respectively. If we divide these values to the difference in the velocities of leading shock wave [2] and gas flow behind it (calculated based on experimental measurements and by assuming of one-dimensional compression of the gas behind the leading shock wave), we obtain the ranges of real induction times for our experiments. They are 0.073 – 0.363 ms and 0.020 – 0.167 ms for mixtures diluted with Ar and N_2 respectively. From our shock tube auto-ignition data (red zone in Figure 5) such induction times correspond to the temperature range 950 – 1050 K and 950 – 1200 K for mixtures with Ar and N_2 respectively. So, the real local temperature observed in experiments is 100 – 200 K higher than that one calculated for post-shock conditions behind the leading shock wave. Thus, experimental DDT observations shows that the local flow temperature of the mixture required for hot spot formation in induction zone of accelerating deflagration are much higher than the local flow temperature obtained assuming one-dimensional shock compression of the mixture behind leading shock wave.

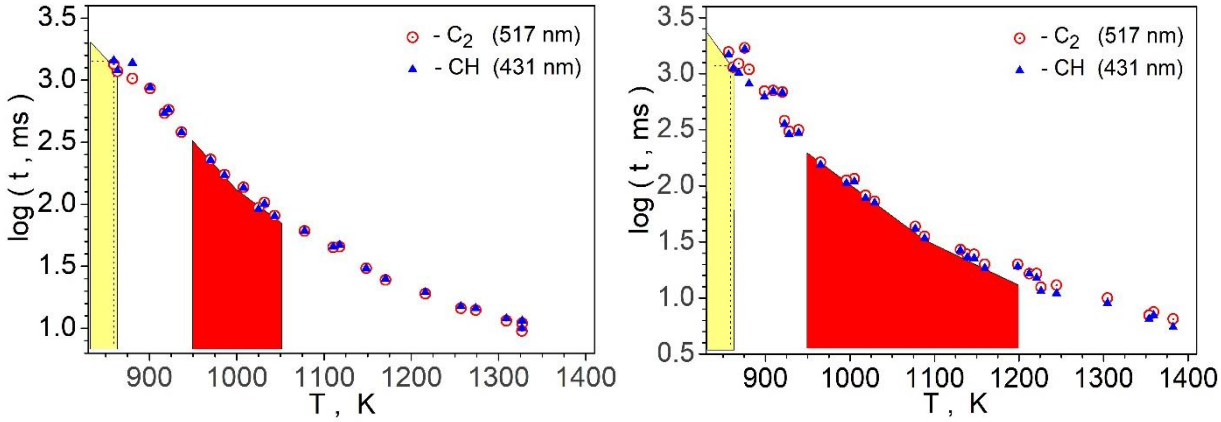


Figure 5. The ignition delay time as a function of temperature for mixtures 8.6% C_2H_2 + 21.4% O_2 + 70% Ar (a), 11.4% C_2H_2 + 28.6% O_2 + 60% N_2 (b)

Thus, the detected hot spot auto-ignition for such post-shock flow conditions cannot take place only due to one-dimensional shock-compressions behind the leading shock wave. Probably, another scenario has to be considered for explaining mechanism of hot spot formation. One can say that at the final stage of deflagration acceleration the flame is attaching to the flow area where the transition to developed turbulent boundary layer was already formed. This transition zone occupy the length about one diameter of tube behind the leading shock wave. Measurements show that the flame is never plane and is extended along the tube to the length up to four tube diameters. It means that the flame front is inclined. The inclined front must generate transverse compression waves cumulating a part of the energy released during combustion into transverse movements of the gas in post-shock flow across the tube. Because the tube wall is not plane it results in formation of the local hot spots in the vicinity of the wall where a part of the energy of transverse gas motion can be converted to the higher temperature and pressure flow regions. This shortens local induction times of unburnt mixture and depending on the mixture sensitivity causes the formation of new re-ignition loci, which can generate weak, transient or strong ignition modes in post-shock flow ahead of the main flame.

4 Conclusions

High-speed video observations of self-luminescence at DDT in a stoichiometric C_2H_2–O_2 mixture with Ar and N_2 dilution at low energy ignition mode were carried out.

Experiments show that then the flame velocity begins exceeding the isobaric sound speed of combustion products one or several hot spots are initiated ahead of the flame. The maximum distance between hot spots and leading tip of the flame was ~ 1d and ~ 0.9d for mixtures diluted with Ar and N_2 respectively. Depending on the mixture sensitivity, weak, transient or strong ignition modes can be generated from the hot spot in post-shock flow ahead of the main flame.

Induction time measurements in shock tube were carried out to analyze the opportunity of hot spot formation in induction zone. It was shown that real local temperature in induction zone between the leading edge of flame front and shock wave should be 100 – 200 K higher than the post-shock temperature deduced by assuming of one-dimensional compression of the gas behind the leading shock wave.

The reason of higher post-shock parameters of mixture in induction zone is additional local transverse adiabatic compression of unburnt mixture near the tube wall, which is generated by inclined flame front.

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