High-speed imaging of DDT in a round tube

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1 Introduction

There are a limited number of experimental [1-8] and a large body of theoretical works that describe and demonstrate the final stage of the flame acceleration in smooth tubes (or channels) with subsequent formation of detonation centers. However, to date there is no unambiguous understanding of the final stage of deflagration to detonation transition (DDT) events. In particular, the question remains about the structure and shape of the flame, the reasons for its acceleration, and the local conditions and exact place of the onset of detonation. All experimental studies [1-8] were done in rectangular tubes in order to apply schlieren and LIF techniques [6] in high-sensitive hydrogen-oxygen mixtures and using strong ignition systems. Only Soloukhin [3] used a round tube for definition of the location of detonation emerging. That allowed experimenters to obtain DDT on short distances but distorted the "classic DDT picture" due to the presence of a strong initial shock wave. In addition, the nature of reflection and interaction of gasdynamic perturbations differs significantly in round and square channel cross sections. In this study, we visualized fast flame propagation, the formation of localized secondary auto-ignitions of the mixture and onset of explosion under DDT process in the classic experimental conditions – by using a smooth transparent long tube and weak ignition system.

2 Experimental setup & details

The experimental setup is simple and consists of a transparent plexiglas tube, two high-speed cameras, low-energy spark ignition system, and gas ramp with vacuum pump (figure 1).

We used a closed tube with a uniform round cross section 60 mm in diameter, 6 m in length, and a wall thickness of 5 mm. Before carrying out an experiment the tube was pumped up to the residual pressure of 10-2 mm Hg and then filled with gas mixture to the necessary initial pressure.

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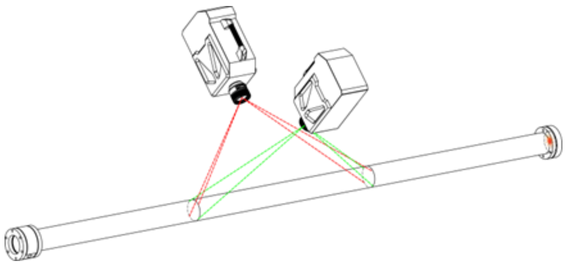


Figure 1. Experimental setup.

We studied stoichiometric mixtures of acetylene and oxygen, with 50% of nitrogen or argon dilution. In preparation of mixtures we used chemically pure (99.9%) gases. Test mixtures were prepared in advance in separate cylinders by the method of partial pressures, and kept for at least 24 hours before use. We utilized weak ignition of the mixture in order to avoid creating a strong leading shock wave. The system had low energy (approximately 0.8 mJ), used a standard automobile spark plug, and was synchronized with two high-speed cameras.

Two identical monochrome Photron Fastcam SA-Z type 2100 cameras were installed in one cross section of the tube, perpendicular to the axis of the tube, at an angle of 90° to each other. We operated at 210,000 fps with 1024 x 72 pixels' resolution. Both cameras were equipped with Tamron SP 24-70 mm F/2.8 Di VC USD lens and Edmund Optics BP 430 nm x 10 nm OD4 50 mm filters. This spectral band corresponds to the luminosity of intermediate CH radicals. Both cameras were located at a distance of 1080 mm from the tube and provided the visible observation length of the tube of 950 mm. Depending on the mixture composition, the visible tube area was at a distance of either 2045 or 2900 mm from the point of initiation. Images taken from one of the cameras were mirrored. The settings of both cameras (start time, recording resolution, frame rate, exposure time of each frame, etc.), as well as the settings of the apertures and the filters on both lenses were the same. Thus, at the same time in the same place (tube section), we received two identical images in terms of their characteristics.

3 Results & discussion

Analysis of image sequences revealed the following regularities. Practically in all experiments we recorded the flame that was shaped like a cone ("paper cone" or "waffle cone"), see figure 2, strongly extended along the axis of the tube. The base of the cone has an irregular shape, is also deformed and elongated along the tube's axis. The term generally adopted in literature to describe the shape of the flame, especially during initial stages of acceleration, is a "tulip form". We found that this characterization is not precise. Figure 2 shows self-illumination of the flame front immediately before the occurrence of detonation in the simultaneous photos taken from two cameras. It is obvious that the flame front has a regular, almost conical shape, which is strongly elongated along the axis of the tube. The length of the flame front cone reaches four tube diameters. The leading part of the flame front (the base of the cone) is deformed from an ideal planar shape and stretched along the axis of the tube. Behind the cone is the tail of a comet shape. In all videos, after the explosion and formation of a detonation wave that propagates forward through the mixture, another detonation wave is clearly visible going in the opposite direction along the unburned mixture inside the cone. This proves that the shape of the flame is exactly conical and inside the cone there is a fresh unburned mixture.

In the final stage of the flame acceleration, there are two variants for the onset of detonation. In the first scenario, when the flame front reaches a speed of about 1150-1200 m/s, one or more auto-ignition centers form some distance (usually up to one tube diameter) in front of the flame. This complex (one or several expanding flame fronts) continues to propagate along the tube for some time (up to 50-60 μs), over a distance of up to 2 tube diameters (see figure 3). Then, because of additional compressions induced by expanding flames there is an explosion of the unburned gas at a single (or multiple) point.

In the second scenario, the occurrence of explosion takes place directly on the edge of the flame front, without formation of ignition centers in front of the flame (figure 4).

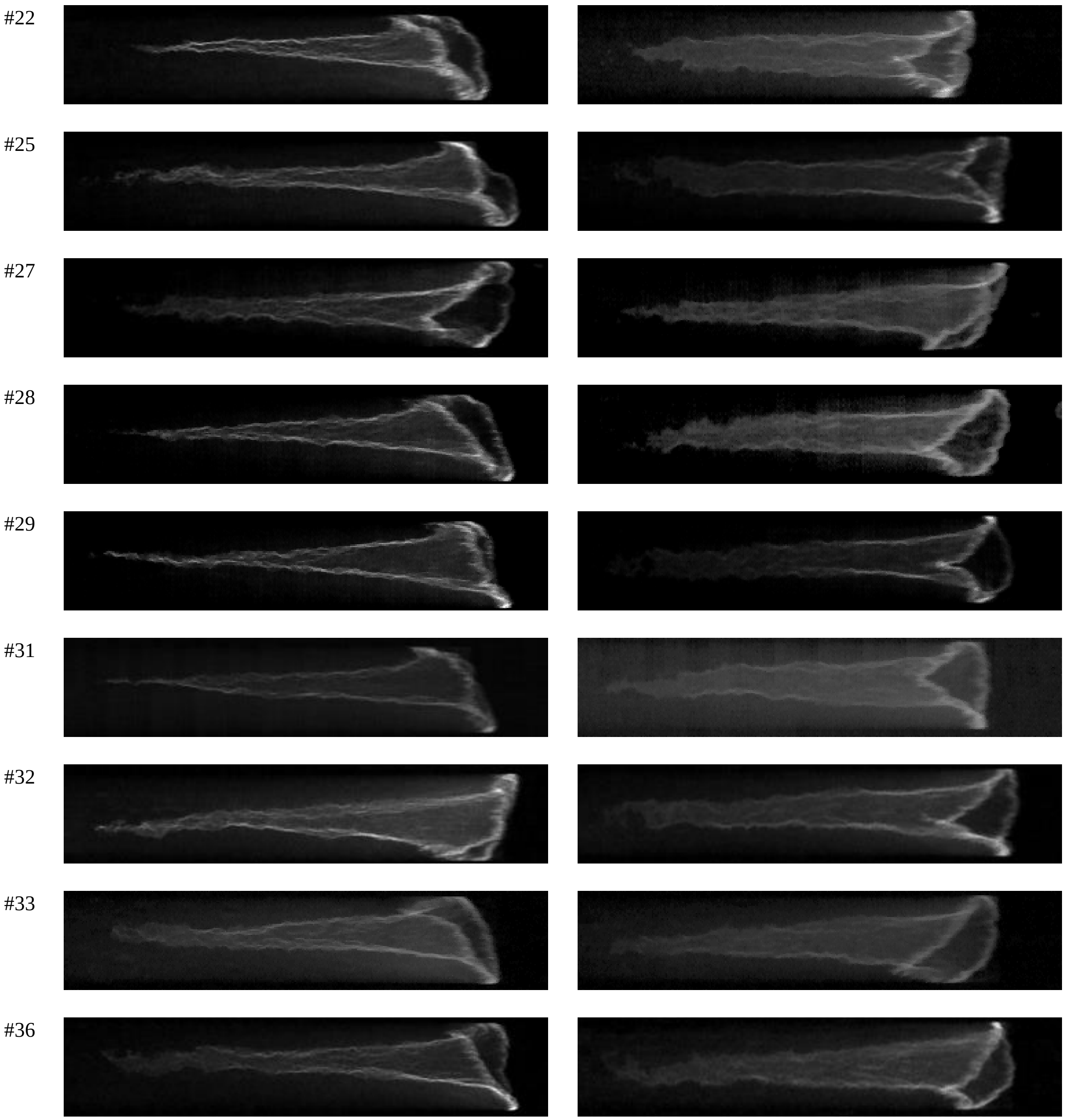


Figure 2. Typical flame front self-luminosity photos. The transverse size (tube diameter) in all images is 60 mm. First raw – experiments number, second raw – pictures from camera 1, third raw – corresponding pictures from camera 2. Mixture - acetylene/oxygen with 50% argon dilution. Initial pressures 16-20 kPa. Frame exposure 3.15 μs.

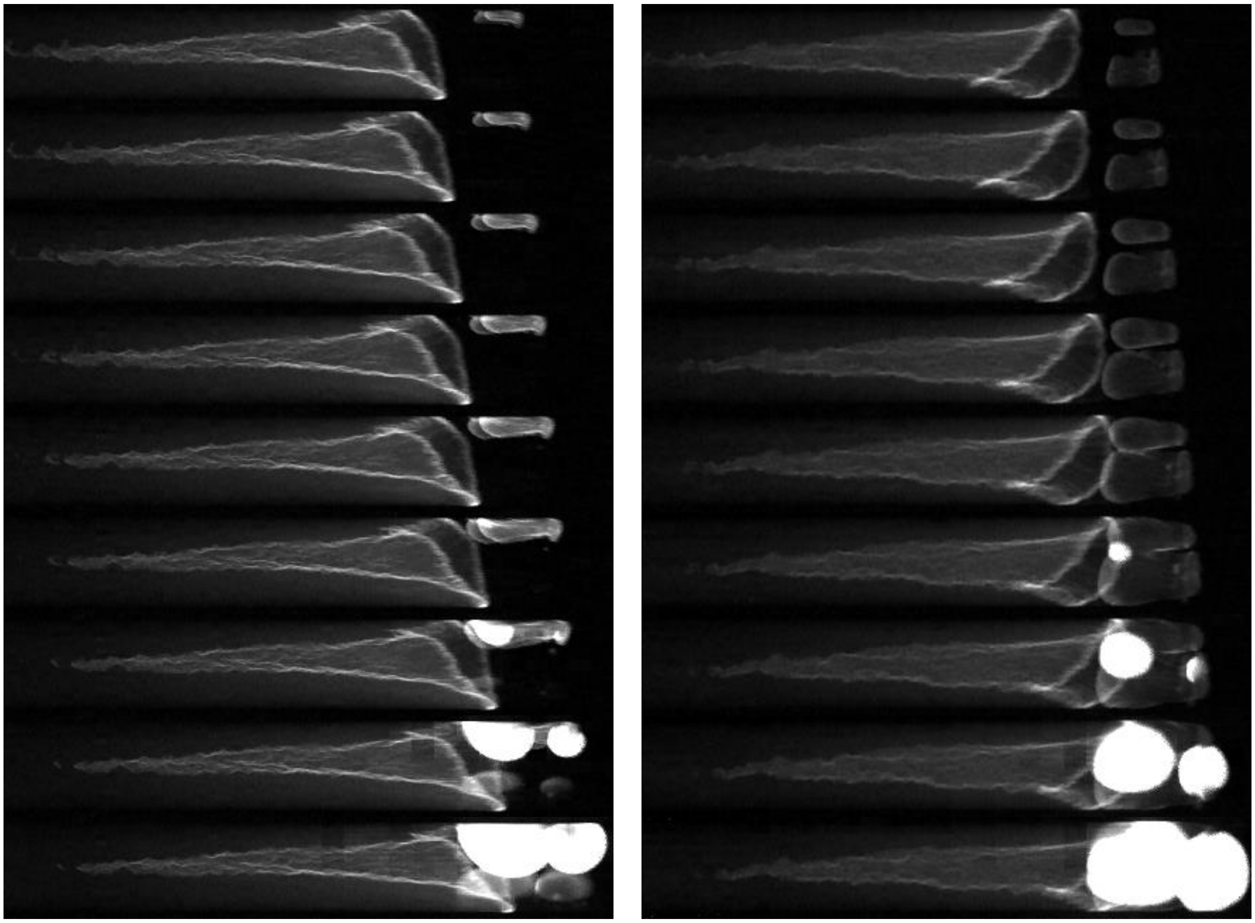


Figure 3. Progress of DDT event and local explosive occur. Ignition and local explosion in front of leading flame. First raw – pictures from camera 1, second raw – corresponding pictures from camera 2. Mixture - acetylene/oxygen with 50% argon dilution. Initial pressures 18 kPa. Frame exposure 3.15 µs, 210 000 fps. The transverse size (tube diameter) in all images is 60 mm.

We attempted to perform 3-D reconstruction using images taken simultaneously from two cameras to localize initial auto-ignition centers, which cause formation of detonation wave and subsequent explosion centers. Such reconstruction introduces certain error associated with the cameras frame rate (210 000 fps in our tests) and the distance that the wave travels between two frames. For the flame velocity about 1200 m/s such error is approximately 5 mm.

Figure 5 present the location of the ignition and explosion points in the tube cross section. In spite of the scatter of experimental data, a pattern can be observed of both ignition and explosion mainly occurring in the gas layer in the vicinity of the tube walls. Axial position is shown in Figure 6 as a relative (normalized by the tube caliber) distance between leading edge of the flame and ignition or explosion center. In some cases, this distance reaches 1.2-1.3 tube diameter. Negative values indicate that the explosion point is at the flame front of an irregular shape and it is behind its leading edge (leading flame tip).

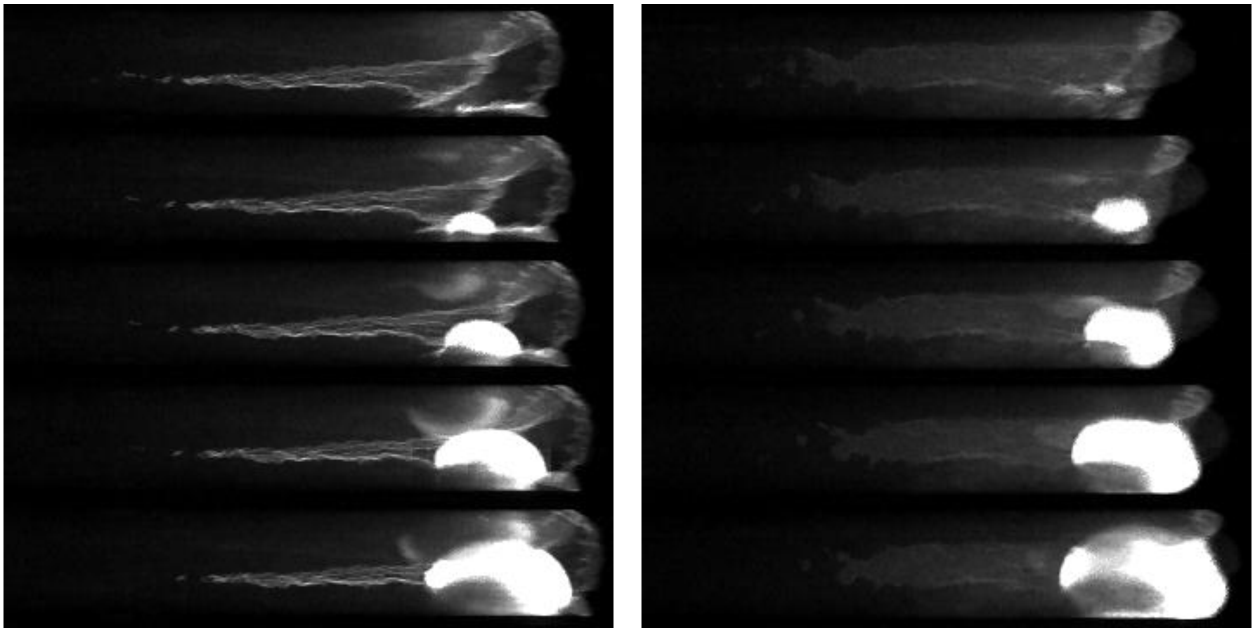
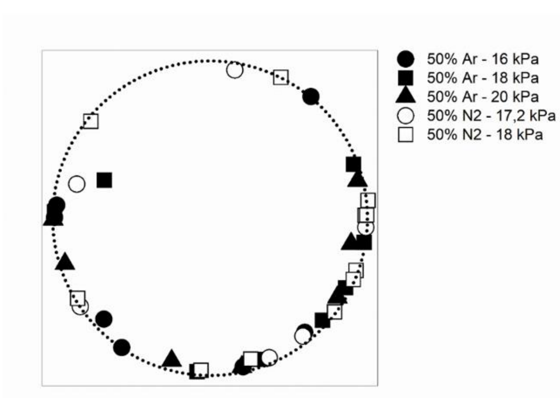
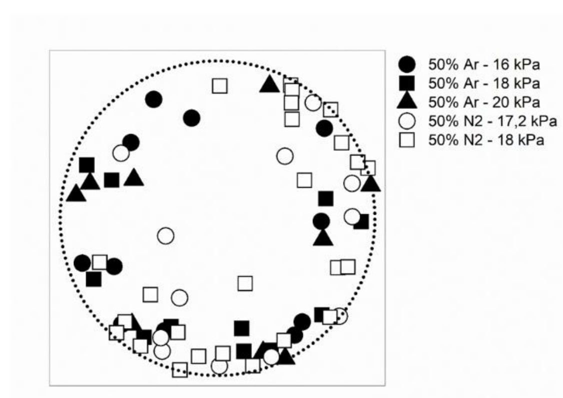


Figure 4. Progress of DDT event and local explosive occur. Local explosion directly on the edge of flame front. First raw – pictures from camera 1, second raw – corresponding pictures from camera 2. Mixture - acetylene/oxygen with 50% argon dilution. Initial pressures 18 kPa. Frame exposure 3.15 μs, 210 000 fps. The transverse size (tube diameter) in all images is 60 mm.

Analysis of the data showed that for studied mixtures (acetylene/oxygen with 50% argon or nitrogen dilution) only in 14% of cases (5 experiments out of 36) the explosion occurred directly at the flame front. In 86% of cases (31 experiments out of 36), ignition first occurred in front of the main flame, and only then one or several explosions lead to the formation of a detonation wave. The quantity of points in figure 5 does not coincide with the number of the discussed experiments since in one experiment several centers of spontaneous ignition or explosion could be registered.



a)



b)

Figure 5. Location of the ignition (a) and explosion (b) points on tube cross section.

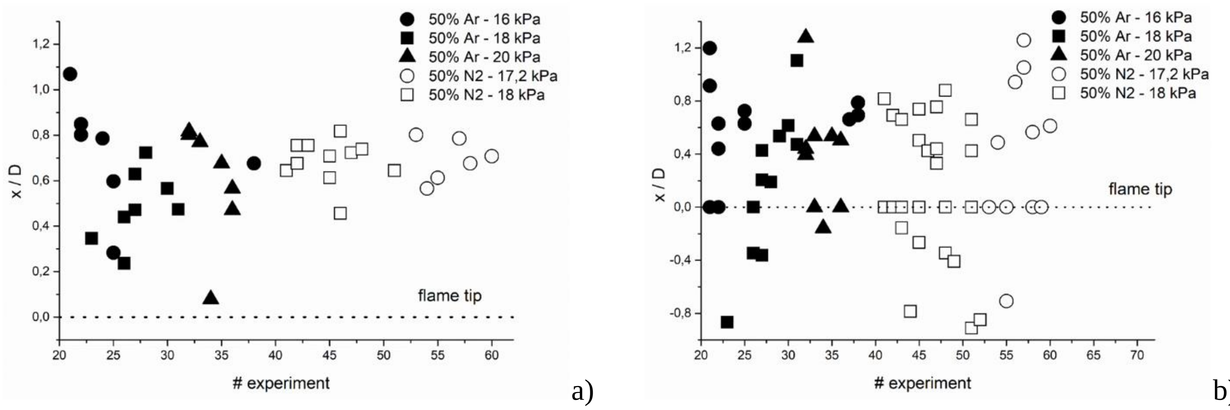


Figure 6. Relative distance from the ignitions points (a) and explosion points (b) to leading edge of flame front.

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