Decaying modes of propagation of detonation and flame front in acetylene–air mixture

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Abstract. Decaying modes of a flame front propagation in narrow channel for acetylene–air mixtures were investigated experimentally using optical methods of diagnostics. Experiments were carried out using an open detonation channel of square cross section with transverse dimension of 3 mm and length of 1000 mm. It was connected to the detonation tube of 20 mm diameter and length of 3000 mm. A galloping decaying propagation of the combustion inside the narrow channel after the entry of a steady Chapman–Jouguet detonation into the channel was registered. It was shown that the propagation of detonation-like galloping combustion is possible in channels of subcritical size. Evolution of the flame front velocity was obtained. The time intervals of gallops and distance intervals were measured. After the decay of the detonation wave, the average velocity of the flame front decreases first to 1000 m/s, and then to 200 m/s.

1. Introduction

Typically, a propagation of detonation in subcritical narrow channels is accompanied by spinning or galloping modes of propagation. These phenomena are due to the intense heat transfer from a reaction zone to the walls, as well as an interaction of the shock front and the reaction zone with a boundary layer.

Detailed analysis of propagation in the spinning mode can be found in paper [1]. The average speed of propagation of the spinning detonation wave is comparable with the velocity \( W \) of Chapman–Jouguet detonation, while the instantaneous values can vary in the range of \((0.6–1.1)W\) [2]. Transition from the diagonal forms of propagation to the spinning ones in rectangular channels are of particular interest [3–5].

Unlike the spinning detonation, the average velocity of the galloping detonation, as a rule, is about \((0.7–0.85)W\) [6, 7]. Parameters of the galloping detonation, such as time interval period and distance interval along the axis, can be found in [8]. The nonstationary modes of propagation of the combustion, including galloping detonation, are described in detail in [9] for ethylene–oxygen mixtures. It was shown that for tubes with diameters of 1, 2 and 3 mm and mixtures with the equivalence ratio of 0.15–0.50 (ER—equivalence ratio, molar excess of fuel) the flame propagates in an oscillating mode. However, the average velocity of such flame front did not exceed 7 m/s. It was shown in [10] that re-initiation of detonation is possible in a narrow channel after the decay of the detonation wave. In these investigations the initial decay of the detonation wave was carried out as a result of the detonation transition into a narrow flat channel.
When working with acetylene, oxygen is most often used as an oxidizer [2,8,11,12]. Mixtures of acetylene with oxygen have the smallest width of the detonation cell, the value of which, depending on the ratio of components, does not exceed 1 mm. For the mixtures of acetylene with air the width of the detonation cell will be higher than 4–5 mm [13]. Thus, the propagation of detonation in channels with transverse dimensions close to 3 mm can be essentially nonstationary in character and differ from the galloping pattern of detonation propagation.

The present work is devoted to a series of experimental investigations of the decaying mode of the flame propagation for acetylene–air mixtures, when the average velocity is significantly lower than the velocity for the stationary Chapman–Jouguet detonation. The aim of the work was to determine the dynamic parameters of the flame propagation for different molar concentrations.

2. Experimental setup
Experiments were carried out using a detonation channel of square cross-section. Transverse dimension of the channel was equal to 3 mm, the length of the channel was equal to 1000 mm. It was connected to the detonation tube of 20 mm diameter and length of 3000 mm (figure 1). The second end of the narrow channel was opened to the atmosphere, so that the pressure inside the channel and the detonation tube was equal to atmospheric pressure. When the end of the channel is opened it allows to avoid the spread of the reflected shock wave perturbations inside the channel.

Acetylene–air mixture was fed into the tube near the closed end of the detonation tube. After a time of 3–4 s after the filling, the mixture was ignited. Ignition was carried out by a spark discharge at the closed end of the tube. The length of the tube was 3 m which is sufficient for the steady detonation of Chapman–Jouguet to be generated before the entry into the rectangular channel.

Acetylene–air mixture allows to carry out the experiments in a rather narrow channel with sufficient luminosity in the visible range. Using the high-speed camera “Videosprint” frames of the reaction zone were obtained. For detailed investigation of a structure of the flame front the Schlieren system based on IAB-451 was used. The frame settings were: frequency of 12500–28100 fps, exposure of 1 µs, resolution was 1280 × 100 pixels.

To register the detonation wave and shock wave inside the channel, two pressure transducers PCB-113A24 were mounted at 100 and 250 mm from the beginning of the channel. Photodiodes FD-256 were used together with the pressure transducers to register the flame front.
3. Experimental results and discussion

Figure 2 shows a series of frames of the flame front and combustion products in the optical range 400–1000 nm after the detonation wave enters the narrow rectangular channel. Data are given for a mixture with ER = 1.4.

As seen from the first frame, the flame front corresponds to the front of the detonation wave. Intensive glow at the top and bottom edges is due to optical reflections on the metal surfaces. The velocity of the flame front between two frames sharply dropped, it was about 1000±50 m/s, which is sufficiently lower than the speed of the steady detonation 1866 m/s [14].

As can be seen from the subsequent frames, the flame front stretches along the axis. At the same time, oscillation of the width of the hot reaction zone is recorded. The smallest width of the luminescence area is 20 mm, and the biggest is 70 mm. The gradual decrease in the average value of the flame front velocity can indicate to a significant role of heat losses on the channel walls. This leads to the complete decay of the detonation wave.

Figure 3 shows shadow frames of the flame front propagation in galloping decaying regime for mixture with ER = 1.4. After 100 µs after the entrance of the detonation wave into the channel, the flame front undergoes changes. Due to the fact that the transverse channel size does not exceed the size of the detonation cell for the acetylene–air mixture (4–5 mm) [13], further propagation of the detonation combustion is not possible.

After 300 µs, the camera records the acceleration of the flame front, which may be caused by an increase of the reaction zone after the combustion front slows down. At the moment of acceleration of the flame front, in accordance with a gas-dynamic discontinuity, two shock waves are formed. One of these waves is directed along the motion of the flame front, and the other is directed in the opposite direction (retonation wave).

Figure 4 shows pressure evolution at the distances of 100 and 250 mm from the entry to the channel. As one can see in figure 4 in these positions, the complete decay of the detonation wave occurs. At the distance of 100 mm, the transducer detects the shock wave and the retonation wave, in accordance with figure 3. A time delay between the shock wave and the flame front was about 30 µs. At the position of 250 mm the pressure transducer registers the shock wave and the subsequent pressure increase due to a new ignition point behind the shock wave.

Figure 5 shows the evolution of the flame front velocity along the channel axis for the mixture with ER = 1.4. Also, the graph shows the change in flame front velocity with time starting from the moment of entry of the detonation wave into the channel. Also, this graph represents a trigonometric cyclic damped approximation. The dependence of the velocity on both parameters has an oscillatory character with damping. In this case, the minimum value of the flame front velocity is the same and is equal to 90–100 m/s for each cycle, which is several times lower.
Figure 3. Shadow frames of flame propagation in decaying oscillating mode, ER = 1.4: 1—damping detonation front; 2—initial shock wave; 3—shock wave; 4—retonation wave.

Table 1. Distance and time intervals of origin of ignition points in the damped galloping regime.

| ER  | $\Delta x$, mm | $\Delta t$, $\mu$s |
|-----|----------------|-------------------|
| 0.9 | 65 ± 4         | 100 ± 8           |
| 1.0 | 70 ± 5         | 200 ± 10          |
| 1.4 | 72 ± 5         | 220 ± 12          |
| 1.6 | 75 ± 5         | 250 ± 15          |
| 1.8 | 80 ± 6         | 300 ± 25          |

for quasi-stationary galloping detonation (0.7–0.85)$W$. Both the time interval and the distance interval between the local accelerations of the flame front gradually increase. The initial value of the period for the mixture with the ratio ER = 1.4 is 220 $\mu$s, while the distance interval is 70–75 mm. This distance corresponds to a distance of 24 channel widths. Later, the period increases to 300 $\mu$s.

The galloping decaying form of propagation of the flame front registered in this study was observed in the range of ER from 0.9 to 1.8. Table 1 shows time and distance intervals for the
Figure 4. Readings of pressure transducers and photodiodes in the narrow channel at positions 100 and 250 mm: 1—shock wave; 2—flame front; 3—retonation wave; 4—secondary shock wave; r.u.—relative units.

Figure 5. Evolution of the flame front velocity along the axis of the channel (from the left-hand side) and time (from the right-hand side), ER = 1.4: red line—trigonometric approximation.

first cycles. The initial time intervals for gallops were varied in interval 100–300 µs, while the distance intervals were about 65–80 mm.
4. Conclusions
With the use of the optical diagnostics methods, the process of propagation of the flame front in the subcritical channel has been studied for acetylene–air mixture. The obtained data made it possible to detect the damping galloping propagation of the combustion in the narrow channel after the decay of the stationary Chapman–Jouguet detonation into the shock wave and the flame front. The initial time intervals for gallops were varied in interval 100–300 µs, while the distance intervals were about 65–80 mm. Immediately after the decay of the detonation wave, the average velocity of the flame front decreases first to 1000 m/s, and then to 200 m/s. The minimum recorded value of the flame velocity was about 100 m/s for each cycle. Thus, in spite of the substantial thermal losses to the channel walls, the propagation of detonation-like galloping combustion is possible in channels of subcritical size.

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