Prechamber initiation of detonation in gaseous mixtures

G Yu Bivol, S V Golovastov and V V Golub
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
E-mail: grigorij-bivol@yandex.ru

Abstract. A process of deflagration-to-detonation transition in propane-butane-oxygen and acetylene-oxygen mixtures, in an open channel with a circular cross section with a diameter of 3 mm, was investigated experimentally. Detonation initiation was carried out by burning the mixture in the prechamber connected to the channel. The prechamber was considered as an extended source for the initiation of the detonation of a finite volume. To measure the velocity of a flame front, photodiodes, installed along the axis of the channel, were used. To determine the boundary conditions at the entrance to the channel, a piezoelectric pressure transducer was used. The influence of the dimensions of the prechamber, equivalence ratio and fuel on the pressure profile, and evolution of the flame front along the axis of the channel are presented. It was shown that, the dynamics of the flame front and shock waves in the channel can occur in different scenarios depending on the geometry of the prechamber and equivalence ratio. Two limit effects of the prechamber detonation initiation in the channel have been analyzed. The pre-detonation distances and the minimal energy of direct initiation of the detonation were determined.

1. Introduction
Prechamber initiation is relevant in the investigation of the dynamics of the flame front and detonation in the narrow channels. One of several prospective applications of micro-scale detonation is in-space propulsion devices. Computational analysis of flame acceleration in narrow channels was carried out in [1]. The topic is of considerable importance not only due to industrial safety concerns, but also the potential application to micro-scale propulsion and power devices [1]. The influence of the geometric parameters of the prechamber on the pre-detonation distance and velocity of the flame front in a connected closed channel was investigated in [2]. The cooling of the combustion products in the prechamber is able to slow down the flame front in the channel.

A main feature of the prechamber is that the energy is used as a source of detonation initiation, which is released during the combustion of a certain amount of its own gas. This energy can be significantly greater than the energy of a direct planar detonation initiation. However, the combustion inside the prechamber is slow. Therefore, a number of compression waves can be formed inside the prechamber as in a connected channel. The dynamics of the compression waves and the flame front in the connected channel is similar to that for the deflagration-to-detonation transition (DDT). However, the pre-detonation distance can be reduced to several tube diameters when the prechamber is used.
The impact of the prechamber on the combustion of detonable gas inside the connected channel is similar to finger flame acceleration. The mechanism of finger flame acceleration in channels at the early stage of burning was studied for slow and fast propane-air flames in [3]. Prechambers of greater diameter are usually used as a method of steady detonation initiation for studies of the detonation propagation in the connected narrow channel. Propagation detonation limits in narrow channels have been studied in [4] focusing on velocity deficits and variations in detonation cell widths. Larger diameter chambers, as well as specially designed chambers, are used for additional acceleration of the flame front. Transmission of single-cell and spinning detonation waves in \( \text{C}_2\text{H}_4/\text{O}_2/\text{N}_2 \) mixtures through a sudden two-dimensional (2-D) expansion was experimentally studied in [5].

The critical conditions for the onset of detonation and the conditions for the propagation of the detonation wave were determined in [6]. A number of attempts have been made to determine detonability limits for various mixtures.

The key element is the presence of the boundary layer and acoustic disturbances that develops along the walls ahead of the flame [7–9]. It was shown that the wall dissipative effects decrease the speed of the detonation wave compared to the Chapman–Jouguet (DCJ) detonation velocity.

As a result of the acceleration of the flame front, compression waves and then multiple reflected waves can occur inside the prechamber. Therefore, at the output of the prechamber, virtually any distribution of velocity-expanded combustion products, pressure or temperature can be generated. Thus, in using such extended sources for detonation initiation as the prechamber of finite volume, it is necessary to strongly define the boundary conditions at the entrance to the channel.

In this paper, we are interested in the pressure profile at the entrance to the channel. The aim of this study was also to determine the pre-detonation distance in the channels of propane-butane-oxygen and acetylene-oxygen mixtures. The aim was to define a minimum energy of direct initiation of detonation by the prechamber method.

2. Experimental set-up

The experimental set-up is shown in figure 1. It consisted of a prechamber (1), connected to an open channel with a round cross section (2), a pumping system (3), a detonable mixture filling system (4), ignition system with a spark gap (5) and a measuring system. The prechamber and the channel were made of brass. The inner diameter of the channel was 3 mm, wall thickness was 7–8 mm. The channel length was 500 mm, i.e. equal to 166 tube diameters. The diameter of the prechamber was 10, 16 or 20 mm. The minimum wall thickness of the prechamber was 8 mm and the maximum 15 mm. The prechamber length varied in the range 7–37 mm.
An open channel was used to prevent the formation of reflected compression waves. A detonable mixture was prepared by partial pressure of the components in a 3 litre vessel. The maximum pressure of the mixture in the vessel was 4 atm. The mixture was maintained for at least 1 hour. The propane-butane mixture used preferably comprised 50% (mol) propane and 50% (mol) butane.

A spark gap was used to ignite the mixture in the prechamber. The aircraft spark gap was used with a planar surface. The energy released did not exceed 0.1 J. The energy released in the spark gap was 2–3 orders less than the energy released during the combustion of the gas mixture in the prechamber. To measure the velocity of the flame front, photodiodes were used, installed along the axis of the channel. The measuring system consisted of 12 FD-256 photodiodes with temporal resolution of less than 1 µs. Conclusions about detonation formation were drawn if the velocity of the flame was close to the velocity of the stationary detonation, CJ detonation.

To determine the boundary conditions at the entrance to the narrow channel just after the prechamber, a PCB 113A piezoelectric pressure transducer was used. The transducer was established at a distance of 30 mm from the beginning of the channel. Since the pressure transducer was not located directly at the entrance to the narrow channel, but at a distance of 30 mm, we determined the pressure profiles listed below as conditional boundary conditions.

3. Summary of the data and discussion

Based on the obtained results we have attempted to define two limiting effects of the prechamber detonation initiation in the channel: the push-effect in the prechamber due to the spreading of the products of combustion with consequent DDT, and direct detonation formation.

3.1. DDT

The detonation is formed in the channel at some distance from the entrance to the channel. Figure 2 shows the dependence of the pre-detonation distance on the equivalence ratio (ER) for the propane-butane-oxygen mixture and the acetylene-oxygen mixture only for the push-effect detonation initiation. The data is given for lean mixtures with ER of less than 1.

For the same value of ER, the distances in the acetylene-oxygen mixture are 30–40% less than in the propane-butane-oxygen mixtures. This is explained by the smaller cell size of the detonation cells in the acetylene-oxygen mixture. For example, in a stoichiometric acetylene-oxygen mixture the size is 0.1 mm, while in the stoichiometric propane-butane-oxygen mixture it is 1 mm, approximately.

The values of ER are limited in figure 2 by the maximal values of 0.5 for acetylene mixtures and of 0.9 for propane-butane mixtures. For excess values of ER, the impact of the prechamber will be considered as having no push-effect but a combination of combustion products and compression waves.

3.2. Direct detonation initiation

In this case, the formed detonation wave enters the channel. However, the first measuring pair pressure transducer–photodiode was installed at a distance of ten tube diameters from the entrance to the channel. Therefore, we would not detect the detonation wave directly at the channel inlet. So, the considered detonation initiation was termed conditionally direct.

Figure 3 shows the experimental data for the possibility of direct detonation initiation depending on the energy value of combustion in the prechamber and the ER for the propane-butane and acetylene-oxygen mixtures. The curve separating the conditions for the direct initiation of detonation (see figure 3) has the form of a parabola with index ~ 3.

The figure 3 shows the points marked by triangles (2). These points correspond to experiments in which the first measuring pair pressure transducer–photodiode does not register a detonation
Figure 2. Pre-detonation distance in dependence on ER for push-effect detonation initiation. 1—acetylene-oxygen mixture, 2—propane-butane-oxygen mixture.

Figure 3. Map of direct detonation formation in dependence on energy, released in the prechamber, and ER of mixture. a, propane-butane-oxygen; b, acetylene-oxygen. 1—no direct formation; 2—formation of detonation between 10 and 40 tube diameters; 3—direct formation.

wave. However, the detonation formation is recorded at the second measuring base, 30 tube diameters.

Data for the oxyacetylene mixture is limited by an ER equal to 1.8. Further increases in the ER lead to a decrease in the prechamber volume. A further decrease is inexpedient because
the dimensions of the prechamber become comparable with the diameter of the channel. The concept of the prechamber in this case can lose meaning.

These energy values for prechamber detonation initiation are substantially higher than the energy for planar or spherical direct detonation initiation: 0.5 J for acetylene [10] and 0.6 J (ER=1) for propane-butane mixture [11]. This is due to the fact that the energy release does not occur in a narrow combustion front plane, whose width is comparable to the induction length, but in a finite volume of the prechamber.

4. Conclusions
It was found that the dynamics of the flame front and the shock waves in the channel can occur in different ways depending on the geometry of the prechamber: deflagration to detonation transition or direct detonation formation. The experimental map of the possibility of direct detonation initiation depending on the energy released in the prechamber and ER for propane-butane and acetylene-oxygen mixtures was obtained.

Acknowledgments
The work was supported by the Russian Science Foundation, grant No. 14-50-00124.

References
[1] Kagan L and Sivashinsky G 2003 Combust. Flame 134 389–397
[2] Lenkevich D A, Golovastov S V, Golub V V, Bocharnikov V M and Bivol G Y 2014 High Temp. 52 890–894
[3] Clanet C and Searby G 1996 Combust. Flame 105 225–238
[4] Ishii K and Monwar M 2011 Proc. Combust. Inst. 33 2359–2366
[5] Wu M H and Kuo W C 2012 Combust. Flame 159 3414–3422
[6] Dupre G, Peraldi O, Joannon J, Lee J H and Knystautas R 1991 AIAA, Prog. Astronaut. Aeronaut. 133 156–169
[7] Ott J D, Oran E S and Anderson J D 2003 AIAA J. 41 1391–1396
[8] Volodin V V, Korobov A E, Golovastov S V and Golub V V 2015 Tech. Phys. Lett. 41 1051–1053
[9] Bivol G Y, Golovastov S V and Golub V V 2015 Tech. Phys. Lett. 41(12) [Pisma Zh. Tekh. Fiz. 41(24) 17–22]
[10] Knystautas R and Lee J H 1976 Combust. Flame 27 221–228
[11] Vasil’ev A A 2012 Shock Waves Science and Technology Library vol 6 (Springer) pp 213–279