Energies of prechamber initiation of detonation in propane-butane-oxygen and acetylene-oxygen mixtures

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1 Introduction

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 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 (below: "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 [1,2].

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 [3] focusing on velocity deficits and variations in detonation cell widths. A channel was formed by a pair of metal plates which were inserted into a detonation tube. Some investigations of DDT in narrow tubes or gaps were undertaken in [4,5]. Detonation was initiated in a large diameter tube before propagating into the narrow tube. Near-limiting propagation of detonation waves under reduced pressures in capillary tubes with inner diameters of around 1 mm using acetylene/oxygen mixtures was studied in [5,6].

Larger diameter chambers, as well as specially designed chambers, are used for additional acceleration of the flame front [7]. In [8], a chamber was used to discharge the combustion product jet that interacted with the flame front. Transmission of single-cell and spinning detonation waves in C2H4/O2/N2 mixtures through a sudden two-dimensional (2-D) expansion was experimentally studied in [9].

Prechamber initiation is relevant in the investigation of the dynamics of the flame front and detonation in the narrow channels. The critical conditions for the onset of detonation and the conditions for the propagation of the detonation wave were determined in [10]. In [11], a parametric study was undertaken of several different combustible mixtures and tubes of different sizes. A number of attempts have been made to determine detonability limits for various mixtures [10,12].

The key element is the presence of the boundary layer that develops along the walls ahead of the flame [13]. Exploring the limits of detonation in narrow channels for diluted mixtures and blends, consisting only of the oxidizer and fuel, the authors of [14] concluded that the decrease in the velocity of the

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detonation wave and, as a consequence, its attenuation, is mainly caused by friction and energy losses in the wall tube. It was shown in [15] that the wall dissipative effects decrease the speed of the detonation wave compared to the Chapman-Jouguet (DCJ) detonation velocity.

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 [16]. 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 [16,17].

It was stated in the detail in [18] that a prolongation in time of the source of ignition has to be taken into account for evaluation of the energy of the direct initiation of detonation. 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 [19]. Particular attention should be paid to the work in [20], where the transition of a laminar flame from the prechamber into the narrow channel was studied. The cooling of the combustion products in the prechamber is able to slow down the flame front in the channel.

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 Figures 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.

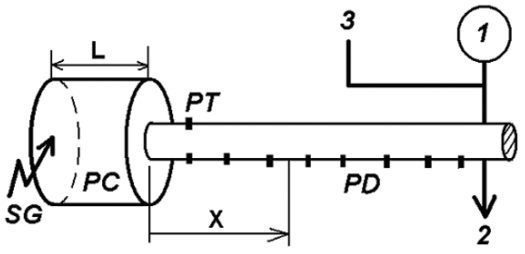

Figure 1. Schema of the experimental setup. PC – prechamber, SG – spark gap, PT – pressure transducer, PD – photodiodes, X – distance along the channel, L – length of the prechamber, 1 – manometer, 2 – pumping system, 3 – mixture filling system.

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*105 Pa. The mixture was maintained for at least

1 hour. The propane-butane mixture used preferably comprised 17%(mol) propylene, 52%(mol) propane and 47%(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.

DDT. The mechanism of the action in the prechamber was explained in detail in Subchapter 3.1.1. 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 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.

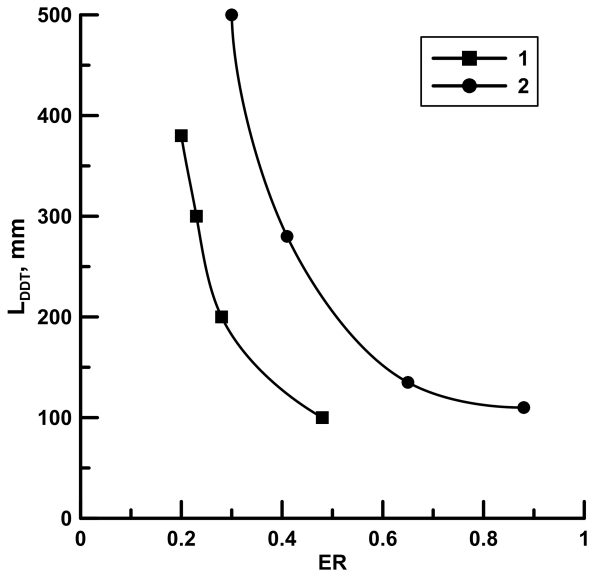

Figure 2. Pre-detonation distance in dependence on ER for push-effect detonation initiation. 1 – propane-butane-oxygen mixture, 2 – acetylene-oxygen mixture.

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.

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" (below – "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, 1) has the form of a parabola with index ~3.

The figure 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 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: 10-2-0.5J for acetylene [21] and 0.6J (ER=1) for propane-butane mixture [22]. 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.

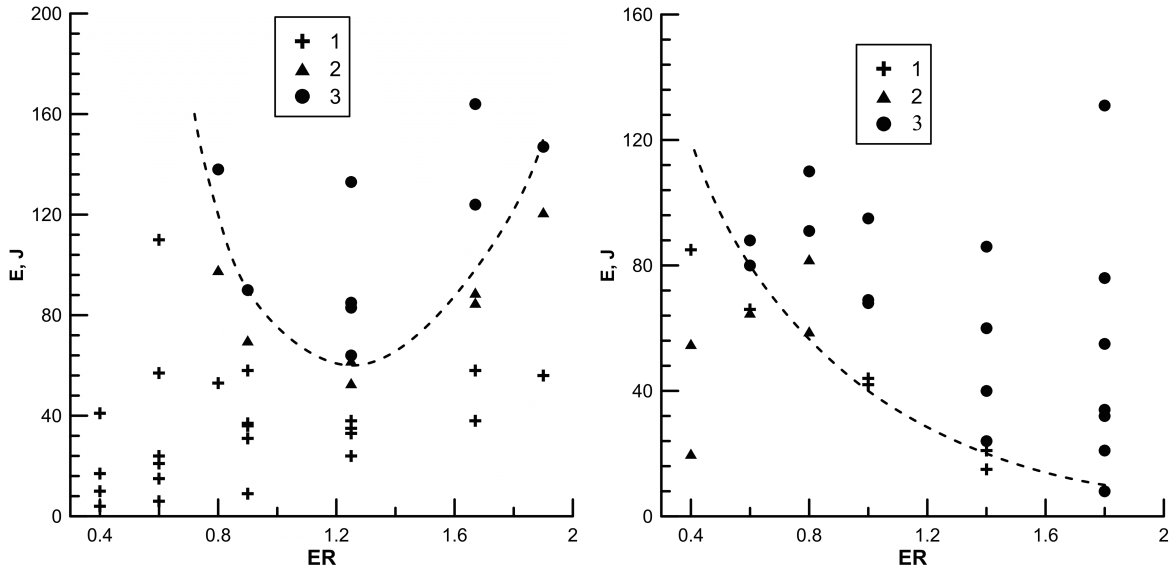

Figure 3. Map of direct detonation formation in dependence on energy, released in the prechamber, and ER of mixture. a, propane-butane-oxygen; b, acetylene-oxygen. 1, no direct formation; 2, formation of detonation between 10 and 40 tube diameters; 3, direct formation.

5 Conclusions

1. 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.

2. 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.

6 Acknowledgments

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