The formation of an overdriven detonation wave in the flow of methane–oxygen mixtures in a channel of variable cross section

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Abstract. Formation of an overdriven detonation wave in methane–oxygen mixtures in a channel was investigated experimentally. The gas mixture was ignited by a spark gap, located at the closed end of the combustion chamber. To create the overdriven detonation wave, a decay of the stationary detonation wave in the transition to a channel with a larger cross-section was carried out. Then, a complex of a shock wave and flame front moved into the channel with converging section. Formation of the overdriven detonation wave with parameters several times greater than those of the Chapman–Jouguet detonation was recorded at the outlet of the conical section. The velocities of the detonation front depend upon the composition of the mixture.

1. Introduction
An overdriven detonation wave is a detonation wave that travels through a shock compressed unreacted mixture. Pressure at the front of an overdriven detonation wave is 1.4–1.6 times that of stationary Chapman–Jouguet detonation. Such excess parameters behind the front of overdriven detonation waves enable detonation spraying of materials with a high melting point [1], improve the efficiency and quality of spraying and production of detonation sprayed nanomaterials. Multi-step detonation was studied in [2] in moving and stationary gas mixtures. Results of detonation diffraction studies are given in [3]. One example of the use of detonation spraying is given in [4]. With the transition to the converging cone, the shock amplitude may increase several times [5]. Attenuation of the detonation wave is investigated in [6, 7]. In our case, the shock wave with the amplitude of 1–1.5 MPa increased its amplitude in the cone and reached that of the Chapman–Jouguet wave. This allowed the overdriven detonation to occur in the cone.

Re-initiation of detonation at the exit from the channel into free space was observed in [8]. The transition of the detonation wave through the expanding channel can occur in two ways: with decay of the detonation wave structure or as continuous transition without wave decay. The results [9] show that the possibility of re-initiation depends on the geometry of the chamber, and the ratio of the channel diameter to the size of the detonation cell. Dependence of detonation propagation conditions on the divergence angle was obtained in [10]. Detonation behavior in an acetylene–oxygen mixture on transition through a cone was studied in [11]. In all cases, the
flame front broke away from the shock wave. The overdriven detonation can be used to create pulse detonation engines [12], including those burning natural gas or methane [13].

The aim of this study was to determine the velocity of the overdriven detonation wave front upon transition to the converging conical section of the detonation tube. The effect of the molar ratio between the components of the methane-oxygen mixture on the parameters of overdriven detonation wave was determined.

2. Experimental set-up
The detonation chamber of variable section consisted of several parts: the initial section, the U-shaped section, the measuring section and the output section. A schematic drawing of the detonation chamber is shown in figure 1.

![Figure 1. Experimental set-up: 1—section of detonation wave formation, 2—pressure and flame gauges, 3—diverging cone, 4—converging cone, 5—U-shaped section, 6—measuring section, 7—spark gap, 8—fitting pipes.](image)

The combustible mixture was ignited in the initial section. The flame front then accelerated to form detonation. The mixture was ignited with a spark discharge produced by an automotive ignition coil. The energy of the spark discharge did not exceed 0.1 J. After the formation, the detonation wave passed into the U-shaped section. This section served to create a stationary detonation wave with Chapman–Jouguet parameters. The length of this section was 400 mm, diameter 16 mm.

After the U-shaped section, the detonation wave passed into the diverging cone with a divergence angle 10°. The initial radius is 16 mm, and the final one is 36 mm (the diameter ratio is 2.25). When experiments on detonation wave propagation were conducted in a channel with a sudden expansion, the diverging cone was not installed. The detonation wave decayed in the measuring section of a larger diameter. Pressure sensors PCB113A and photodiodes PD 256 were placed along the chamber wall to record detonation waves or compression wave / flame front complexes. The distance between the sensors was 60 mm. Optical wires were located in same cross section as the pressure sensors. The length of the measuring section was 400 mm, diameter 36 mm. In our ongoing experiments, the angle of convergence in the measuring section was 8°. The length of the output section was 300 mm and the exit diameter was 21 mm. The section had an open end. The initial pressure within the combustion chamber prior to each
experiment was equal to the atmospheric pressure. The initial temperature was equal to the ambient temperature of 300 K.

To determine the size of the detonation cell, we used a soot-coated copper foil coated. The components of the mixture were either mixed in advance in a separate volume, or were fed separately into the detonation chamber just before initiation. The first regime was called “premixed, and the second, pulsed. The cell size was measured only in the premixed regime. Mixture components were fed separately using two supply lines with fuel (methane) and oxidant (oxygen or oxygen / nitrogen). The gas flow rate was determined using float flowmeters. The coefficient of molar fuel excess (equivalence ratio, ER) varied from 0.75 to 2.35. To analyze the effect of gas mixture flow, a series of experiments was carried out with a stationary gas mixture. We used a premixed mixture of methane with oxygen and air. The mixture was prepared in a 40-liter cylinder. The full cylinder pressure was 5–8 atmospheres. The mixture was kept for at least 24 hours.

3. Experimental results
To achieve high parameters of the overdriven wave, we should start with a decay of the detonation wave. To achieve this, the ratio between the mixture components was compared in the pulsed regime. Detailed results for the ratio of ER = 1.35–1.45 for the diverging cone (a) and sudden expansion (b) are shown in figure 2.

![Figure 2. Pressure readings in the measuring section: a—moving mixture with conical entrance, b—moving mixture with sudden expansion.](image)

At the entrance of the measuring section, the detonation wave has already formed. The pressure sensors located in the measuring section recorded a constant detonation velocity of 2600 m/s, and the photodiodes did not record any lag between the flame front and the shock wave. That is, the shock wave / flame front complex was stable.

As the detonation wave was passing from the measuring section into the output section, its front pressure grew to 2.8 MPa. Measurements of the detonation cell width with a smoked foil gave the value of 6 mm for ER = 1.45 (figure 3). When the detonation wave was propagating in the moving mixture through the diverging cone, no detonation front decay was recorded. Just as in the previous case, there the pressure increased to 2.8 MPa.
However, when the entrance in the measuring section had a sudden expansion, the detonation wave was observed to decay. The pressure sensor detected a 1 MPa shock wave. In the process of wave propagation through the measuring section, the shock amplitude increased to 2 MPa. The velocity of the shock wave in the measuring section was 1500 m/s. The photodiodes placed in the same cross section as the pressure sensors recorded a lag 30–50 µs between the flame front and the shock wave. The amplitude of the pressure shock wave is less than the corresponding value of the Chapman–Jouguet detonation wave. This leads to the conclusion that there was no detonation after moving from the narrow part of the chamber to its wide section. After passing through the converging cone, the pressure sensor detected a 7 MPa detonation wave.

4. Discussion
The experimental data allow us to analyze the effect of mixing and presence of flow on the detonation wave and the process of its decay. The increase in the detonation cell width by varying the ER reduced the detonation or shock velocity, if the detonation wave decayed. Figure 3 shows the wave velocity as a function of ER. As expected, the deviation from the ER = 1 led to the detonation wave decay, after which the wave velocity decreased.
However, if the detonation wave decayed, the presence of the converging cone led to the initiation of overdriven Chapman–Jouguet detonation. The resulting pattern also confirms that the velocity reduction is attributed to the decay of detonation rather than to other effects. The maximum velocity is shifted toward the ER values greater than 1. This is probably due to the increase in the speed of sound in the initial mixture.

5. Conclusions
Parameters of detonation waves propagating in a channel of variable section in methane-oxygen mixtures have been studied experimentally. Parameters of overdriven detonation were measured. The wave parameters correspond to those of fixed Chapman–Jouguet detonation at ER close to stoichiometric.

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