Calculation of special modes of detonation propagation in tubes

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1 Abstract

Results of calculation of the multi-step mode of detonation propagation (MSD) in a pulsed detonation engine with a detonation chamber of varying cross-section are given. The calculation has been mode analytically in one-dimentional approximation with the method, used for the calculation of one-diaphragm shock tube, taking into account a change of cross-section at the place of diaphragm. Satisfactory agreement with experimental data in a mixture of methane and oxygen has been obtained.

2 Introduction

The cases are known when at detonation propagation in pipes areas of abnormal elevated pressure appear. The pressures can exceed well over Chapman-Jouguet pressure and can lead accidentally to the tube destruction. These phenomena can be explained by the appearance of unsteady system "shock wave-combustion zone" during formation and propagation of detonations.

Investigation showed that upon weak ignition of the combustible mixture in a tube, the flame front propagates, accelerating gradually, and, by acting like a piston, causes the formation of one or several shock waves one after the other ahead of it. Depending on the mixture composition, tube diameter, and roughness of tube walls, various laws of front acceleration and, accordingly, distribution of flow parameters are feasible between the front of the shock wave and the flame front. Transition to detonation takes place as a result of explosion of a hot gas volume which is heated by the shock wave and trapped between the shock wave and the combustion zone. Part of the created wave is detonation wave, which travels forwards along the tube behind the shock wave and overtakes it. Here, the detonation wave, as pressure and velocity measurements indicate, is always formed as the wave with higher parameters behind it in comparison with C-J wave in initial mixture, because it is formed in previously compressed and heated mixture [1, 2]. The velocity of the wave then decreases quickly and the pressure drops to the value in the C-J wave.

If one assumes that the length of the tube is to short and the formation of detonation behind the incident shock wave, then detonation occurs near the end of the tube, at the moment of reflection from far the end wall (Fig. 1, b). The pressure at that end wall increases by many times C-J pressure [3, 4].

The formation of detonation in the gas compressed and heated by a shockwave was named multi-step detonation [5]. Such a MSD mode can arise incidentally and uncontrollably both in a short detonation

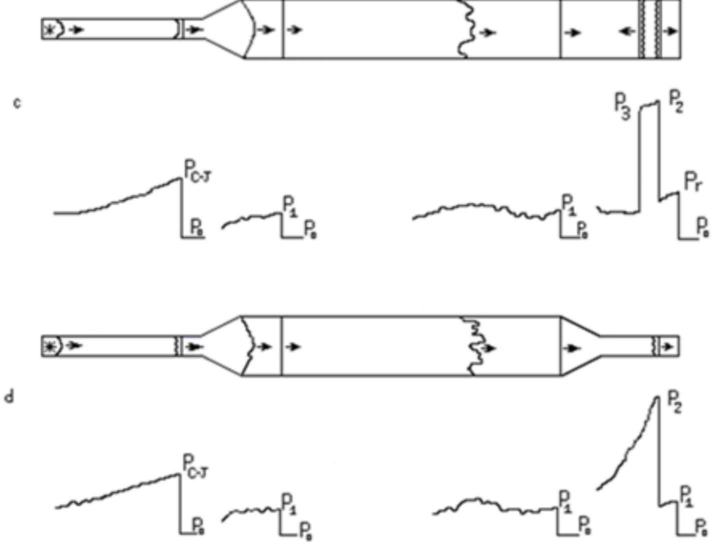

Figure 1: Transition from deflagration to detonation in tubes: a - long tube of constant cross - section with closed end, b - short tube of constant cross - section with closed end, c -tube with converging cone with closed end, d - variable cross-section tube with opened end, P0 - initial pressure, P1 - pressure behind shock wave, P2 - pressure behind detonation wave, P3 - pressure behind retonation wave, P C - J - Chapman - Jouget pressure, Pr - pressure behind reflected wave.

tube (near the end of the tube behind the reflected shock) in the tubes with constant cross-section, or in a long tube (via deflagration-to-detonation transition).

It has been shown that the MSD mode can reproducibly be localized by introducing a variable cross-section tube in a longer tube of a constant cross-section [5, 6, 7]. Stabilization of place of detonation formation has been achieved by creation of unsteady complex "shock wave - flame" in the expanding cone by diffraction of detonation wave. Then the formation of detonation takes place or near the closed end wall behind the reflected shock wave (Fig. 1, c) , or at the converging cone in the tube with open end (Fig. 1, d).

In the description of the figure we also make a literature reference [2].

This mode of detonation in the tube with open end has be used for operation of PDE in a frequency mode. The MSD mode of operation, obtained in the experiments with PDE with detonation chamber with variable cross-section and valveless system of charge gives parameters of flow much higher then at the operation in the simple detonation. The experiments have been made in the mixture of methane with oxygen. The MSD mode of PDE operation is not yet repeated experimentally, as we know, in some other works, nor calculated numerically less the paper [8], where the MSD mode was simulated but in stoichiometric H2-O2 mixture at a single shot.

This paper presents the simple analytical method of calculation of multi-step detonation made of PDE operation, which has been found experimentally in [5, 6, 7].

3 Initial data for calculation

Figure 2 shows a schematic of the variable cross-section DCC and in which experiments on MSD mode were made. The components of the combustible mixture are separately introduced and mixed in a transition section. Diameter and length of the transition sections are selected so that a stationary detonation forms in it. In dependence on the mixture composition detonation chamber can be operated as in the simple detonation mode or in the MSD mode. The additional requirements to the diameter for the MSD mode is that the detonation wave, as it passes through the expanding cone and enters the main section of DCC, decouples into a shock wave and flame front. As the decoupled wave system propagates towards the cylindrical section, separation distance between the shock and flame front increases.

In the converging cone, the shock wave undergoes Mach reflection and the gas is compressed to a state at which ignition occurs. As the wave system enters the narrower channel, it gives rise to a multstep detonation with the products having parameters higher than those of the CJ parameters in the initial detonation wave.

Experimental studies of the MSD mode were conducted with the methane-oxygen mixture at initial pressure P1 = 100 kPa and temperature T1 = 300 K. Diameter of the DCC transition chamber equals

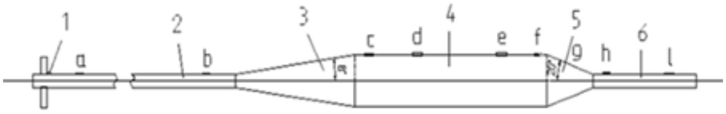

Figure 2: Detonation combustion chamber of variable cross-section: 1 - ignition, 2 - forchamber, 3 - expanding cone, 4 - main section, 5 - converging cone, 6 - final section; a, b, c, d, e, f, g, h, l - position of pressure gauges and photo diodes.

16 mm. The main chamber equals 65 mm in diameter and 1 m long. The expansion angle of the transition section was 16 grad. Coefficient of excess of oxygen is equal 1.4. Calculation has been spent for detonation experiments in methane-oxygen mixtures with $\alpha = 1.4$. The initial data (Table 4) are resulted for frequency 1 Hz. Thus velocity of filling the tube with a gas mixture was 85.5 m/s, and velocity of filling of the basic chamber was 5.3 m/s.

4 Analytical calculation

Calculations were made by the analytical method used for shock tube calculations, by studying of wave patterns appearing at propagation of shock wave through diverging and converging corns of the tube. Detonation first is decoupled in the expanding cone and then reinitiated in the converging cone. It was suggested that detonation wave in the forchamber propagates with velocity taken from experiment. Parameters of burnt gases behind it were determined with usual formula [9].

Calculation of decoupling of detonation wave at its exit in extending channel has been conducted by a method of breaking of arbitrary discontinuity taking into account a change of diameter of a pipe at the rapture place. It has been supposed that the decoupling occurs at a junction of the forchamber and the main section. The following wave patterns were considered: in the main section (analogue of the chamber of low pressure) the appearance of non-stationary complex-shock wave-combustion zone. In the transition forchamber a non-steady rarefaction propagates following by steady flow in the expanding cone.Shock adiabatic curves for passing waves were calculated for the perfect gas. Equations for unsteady rarefaction waves and gas dynamic functions for steady flows were used. The points of intersection of shock polars in pressure-velocity diagram were found. The result is parameters of the shock wave in the main section.

Calculation of parameters of gas for the shock wave at its reflexion on an input in a converging cone has been made in the following manner: the shock wave is reflected, gas behind it is accelerated in the stationary mode until the speed of sound in a narrow section, and then in a non-stationary rarefaction wave till the speed of gas behind the passing shock wave.

These calculations were spent by a method of shock polars similar to the calculation of breaking of a detonation wave at an exit in extending part. It was supposed that the imagined diaphragm is located in a narrowed part of the channel, the final section is a chamber of low pressure, in which combustion products extend.

As the result of this part of calculation we have pressure and temperature behind reflected wave in the main part. At last, the value of velocity of reinitiated detonation wave had been calculated as C-J velocity at the increased pressure and temperature behind reflected shock wave, using usual formula [9]. This detonation propagates into the final section. The results of calculation and experimental are given in table 4.

Calculated data for detonation velocity D4 in final section is given in table 4. Satisfactory coincidence

Table 1: Experimental and calculation parameters of gas flow for detonation and multstep detonation mode in the detonation chamber of the variable cross - section. P2 - pressure behind leading wave; P5 - pressure behind reflected wave, Ws - shock wave velocity; D - detonation wave velocity.

Measurement place	La-b	Cross-section f	Cross-section f	Cross-section h	Le-f, 151 mm	Lh-l, 62 mm	Remark
α	D, m/s	P2, MPa	P5, MPa	P2, MPa	W's, m/s	D4, m/s	
1.4	2250 ± 30	3.0 ± 0.2	1.3 ± 0.7	3.2 ± 0.1	2200 ± 30	2470 ± 40	Detonation experiment
	2250 ± 30	1.5 ± 0.1	4.0 ± 0.4	5.0 ± 0.5	1200 ± 80	2750 ± 200	MSD experiment
	2250	1.25	7.3	5.7	880	2766	MSD calculation

with experiment is received for the velocity of detonation D4 in the final section. The calculation pressure P5 behind the shock wave is higher than in experiment. This is probable due to the use of simplified formula for detonation. The mechanism of propagation of the detonation wave formed behind the reflected shock wave into the final section did not also taken into account.

5 Conclusion

Simple method for the calculation of multi step detonation mode of PDE operation is suggested and verified for experiments in stoichiometric methane - oxygen mixture. The results are quite satisfactory agree with experimental ones.

6 Acknowledgment

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