

Multi-Step Detonation Mode and Its Application

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INTRODUCTION

We describe a newly demonstrated mode of combustion, the multi-step detonation, and the special detonation combustion chamber (DCC) which together allow realization of a repetitively pulsed detonation facility in which, with a probability of 0.995, each pulse is a multi-step detonation (MSD). Applications of this new MSD mode are discussed, including spraying of protective coatings.

It is possible, for a given initial state, to produce flow parameters more extreme than those behind a stationary detonation wave if one can bring about a wave precompression of the unburned gas prior to its transit by a detonation wave. A shock wave not itself strong enough to produce ignition can be used to bring about this intermediate compression, which would then be followed by a detonation wave with its associated combustion. We term this mode of combustion a 'Multi-Step Detonation', or MSD.

1. COMBUSTION BY A MULTI-STEP DETONATION PROCESS

The parameters of the combustion products depend on the parameters of the combustible mixture immediately before the detonation wave (the initial conditions for the detonation). Therefore, if the combustible mixture can be compressed before the detonation wave arrives, then the higher parameters of this precompressed state become the initial conditions for the detonation itself. In such a case the parameters of the detonation products would correspond to a CJ point laying on a different detonation adiabetic with higher characteristics. To achieve this mode of burning one needs first at least one primary shock wave to produce the intermediate compression of the combustible mixture, and secondly, an additional shock wave able to initiate a detonation in this compressed mixture.

In the usual detonation process (see Fig. 1) the gas is compressed by a shock wave on shock adiabetic curve H_1 and ignition occurs, followed by an increase in temperature and decrease in pressure. Complete combustion is represented by point C_1 on that detonation adiabetic J_1 which is appropriate to the Chapman-Jouguet parameters for a steady detonation. If however the initial shock wave is not sufficiently strong as to cause ignition, then a second shock wave may be introduced into the compressed but unignited gas behind the first shock wave. This second shock is represented by shock adiabetic H_2 . It will produce ignition and the system will pass to that higher detonation adiabetic J_2 which corresponds to the more extreme initial parameters (point A_2). The final state C_2 for this multi-step detonation will clearly lie above the final state C_1 for a single stationary detonation.

Such a multi-step detonation mode may occur accidentally and uncontrollably both in a short detonation tube, where it could happen near the end of the tube behind the reflected shock, or in a long tube, where it could be an intermediate step in a deflagration-to-detonation transition. The authors have shown [1-2] that this new mode of combustion may be reproducibly localized by introducing a length of variable cross-section tube in a longer tube of constant cross-section.

2. DETONATION FACILITY

Figure 2 is a schematic of the variable cross-section chamber and the processes which occur within it. The combustion gases are separately introduced and then mixed in a preliminary section whose diameter and length are selected so that a stationary detonation is formed in it. An additional requirement on the diameter is that the detonation as it passes through the expanding cone and enters the main part of the combustion chamber must decouple into a shock wave and following flame front, where the separation between these will increase with further propagation through the cylindrical part.

In the converging portion of the chamber Mach reflection occurs and hence the gas undergoes further compression sufficient to cause ignition. As the wave system exits into the narrower channel, it is in the form of a multi-step detonation with the products having parameters more extreme than those of the C-J parameters of the initial detonation. It may be noted that in our earlier work [1, 2, 5] what is here termed a multi-step detonation was referred to as a "double non-stationary discontinuity"; the new name is more physically descriptive.

Thus the authors have discovered a configuration in which the MSD mode of detonation reproducibly occurs at a given point along the detonation tube. This facility can be operated in either a single pulse mode or in a repetitive mode with a frequency up to 10 Hz. The operating time is not limited and produces an exit gas flow with parameters much more extreme than in the case of usual detonation mode.

Experimental and theoretical studies of the MSD mode were made in methane - oxygen, hydrogen - oxygen and hydrogen - air mixtures. The MSD concentration limits are found to be narrower than for a CJ detonation with the same initial conditions. Since the temperature of the combustible mixture changes in the repetitive mode, the influence of the frequency of operation on the concentration limits was studied.

Depending on mixture composition, the detonation in the main chamber occurred either in the CJ or in MSD mode. For methane-oxygen mixtures with $\alpha < 1.2$, detonation occurred in the main chamber with the average propagation velocity in the last section $D = 2300 \pm 20$ m/s (for $\alpha = 1$), and $D = 2280 \pm 30$ m/s (for $\alpha = 1.2$). The range of α from 1.2 to 1.4 appeared to be relevant to transient processes. In most cases, at $\alpha = 1.2$, the detonation wave emerged in the main chamber. However, sometimes this did not occur, and the MSD mode was observed along the entire length of the main chamber. At $\alpha \geq 1.4$, MSD mode was characteristic along the entire length of the main chamber, and this fact was a requisite condition for the emergence of the MSD mode. At $\alpha > 1.8$, the non-stationary complex occurred in the main chamber, while the MSD mode was not realized. In this case, the pressure in the shock wave was less than 1.0 MPa, while the average propagation rate at the inlet up to the amplification unit was $W_s < 800$ m/s. Therefore, the concentration limit of the MSD mode existence in the DC of variable cross-section was in the range of $1.4 \leq \alpha \leq 1.8$, when using methane-oxygen mixtures.

In the MSD regime described above, the gas parameters averaged over the cross-section of the DC channel are represented in Fig.3 by curve 0-1-2-3-4-5-6-7-8. The parameters of the detonation products, when a detonation wave is produced in the main chamber and amplified in the convergent channel, are given by curve 0-1-2-3-6-8. Curve 0-1-2-3-4-6-8 characterizes the gas parameters in the absence of explosion or detonation in the amplification unit behind the incident shock wave. This pattern is observed with the incident shock wave is relatively weak.

Table 1

Gas flow parameters for MSD and detonation process in the detonation chamber initially filled with the methane-oxygen mixture (repetitive mode 0.5 – 2 Hz)

α	D m/s	P_2 MPa	W_s m/s	P_2 MPa	W_s m/s	Remark
1.8	2130±30	1.2±0.1	1010±100	3.9±0.3	2550±200	DND
1.6	2170±30	1.3±.07	1120±70	4.7±0.5	2800±300	DND
1.4	2250±30	1.5±0.1	1200±80	5.0±0.5	2750±200	DND
1.4	2250±30	3.0±0.2	2240±30	3.2±0.1	2470±40	Det
Point	L_{a-b} , 240mm	f	L_{f-g} , 151mm	h	L_{h-l} , 62mm	

Table 1 presents the gas flow parameters for the MSD and detonation processes in the DC (repetitive mode 0.5 – 2 Hz), when methane-oxygen mixtures are used. Here, P_2 is the pressure at the front of the incident shock wave in the respective cross section, W_s is the shock velocity, and D is the detonation velocity. The significant increase of pressure P_5 in all MSD regimes, in comparison with the detonation regime is evident.

3. APPLICATION OF THE MSD MODE TO SPRAYING OF PROTECTIVE COATINGS

The detonation method as now commonly used produces a protective coating which will survive in more severe environments than coatings produced by other gas-thermal methods. Practically all installations used for detonation spraying contain mechanical valves and are therefore restricted to essentially single pulse operation [4]. Another limiting factor of present facilities is their restriction to use of acetylene, which is expensive. To improve performance, upgraded detonation chambers have been suggested which do away with the valves and which use less expensive hydrocarbon fuels, e.g., methane, propane, petrol, etc. [3].

The cost of detonation coatings can be further decreased by using the multi-step detonation mode.

For this application the combustion chamber is modified to provide additional ignition via a bypass line [2] as shown in Fig.4. Ignition takes place 50 microseconds prior to the arrival of the shock at the place of the ignition, and use of this technique gives a 0.995 probability of formation of the MSD mode.

This detonation combustion chamber operated in the MSD mode was used to spray an aluminum oxide coating on a steel substrate; granulation of 40-50 and 50-63 microns was produced. The dependence of microhardness, adhesion and α -phase content on the depth of charging and the composition of the combustible mixture were investigated. Three quantities were held constant in the study; the consumption of the methane -

oxygen mixture ($5.6 \pm 0.1 \text{ m}^3/\text{hour}$), the pulse repetition rate ($0.5 \pm 0.01 \text{ Hz}$), and the stand-off spray distance L ($90 \pm 1 \text{ mm}$). Microhardness and α -phase content were determined.

It was found that, relative to a conventional detonation technique, the MSD mode coating has lower adhesion characteristics, a higher α -phase content, and up to 30% greater porosity. The α -phase content increase is due to fewer of the Al_2O_3 particles being melted and the initial α -phase content therefore being preserved. Such variation in the α -phase is consistent with the lower adhesion observed. An increase in the α -phase content is known [5] to lead to an increase in thermal resistance. A detonation facility operated in the MSD mode for deposition of Al_2O_3 protective coatings can achieve up to 70% higher content of the α -phase relative to other plasma and detonation techniques and maintain an adhesion strength to a steel substrate of at least 16 MPa.

3. CONCLUSION

1. It was shown, that it is possible, for a given initial state, to produce flow parameters more extreme than those behind a stationary detonation wave if one can bring about a wave precompression of the unburned gas prior to its transit by a detonation wave. A shock wave not itself strong enough to produce ignition can be used to bring about this intermediate compression, which would then be followed by a detonation wave with its associated combustion. We term this mode of combustion a 'Multi-Step Detonation', or MSD.

2. The authors have shown, that this new mode of combustion may be reproducibly localized by introducing a length of variable cross-section tube in a longer tube of constant cross-section.

3. Experimental studies were performed in a DC of variable cross-section for $\text{CH}_4 + 2\alpha\text{O}_2$ mixture with pulse frequency of 0.5-10 Hz. It was found, that the pressure in the MSD was higher than in the detonation regime. At the repeated mode of generating detonation waves, the concentration limits of the MSD origin are narrower in comparison with a single mode generation of detonation waves. The concentration limit of the MSD existence in a DC of variable cross-section was within the range of $1.4 \leq \alpha \leq 1.8$, when using methane-oxygen mixtures.

4. Current investigations show a possibility to apply the MSD mode for practical purposes, in particular, for spraying of protective coatings.

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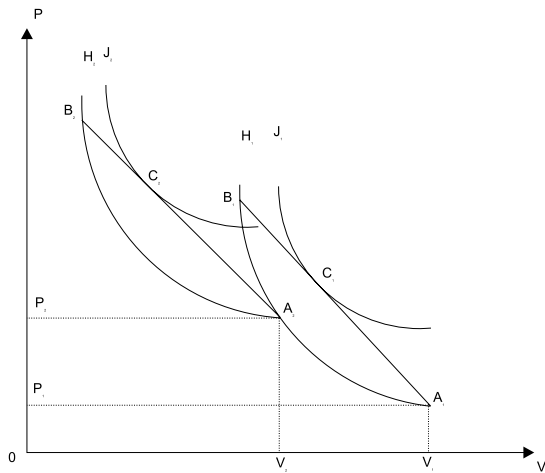


Fig.1 Hugoniot adiabetic curves for different initial states of combustible gas

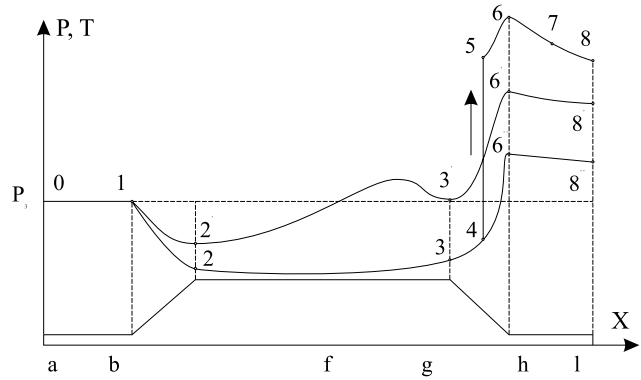


Fig.3 Gas pressure P and temperature T at the shock wave front averaged over the channel cross-section

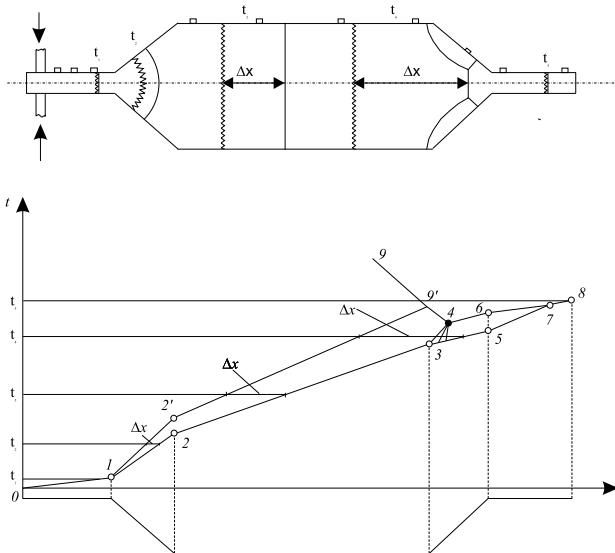


Fig. 2 Wave pattern at different times and X-t diagram of MSD mode in DCC --- shock wave, ^^^ - combustion front, Δx is a distance between shock wave and flame front, 1-2-3-5-7 - shock wave, 1-2'-9' - flame front, 9-9' - retonation wave, 4-6-7-8-9' - secondary detonation wave, 7-8 - multi-step detonation

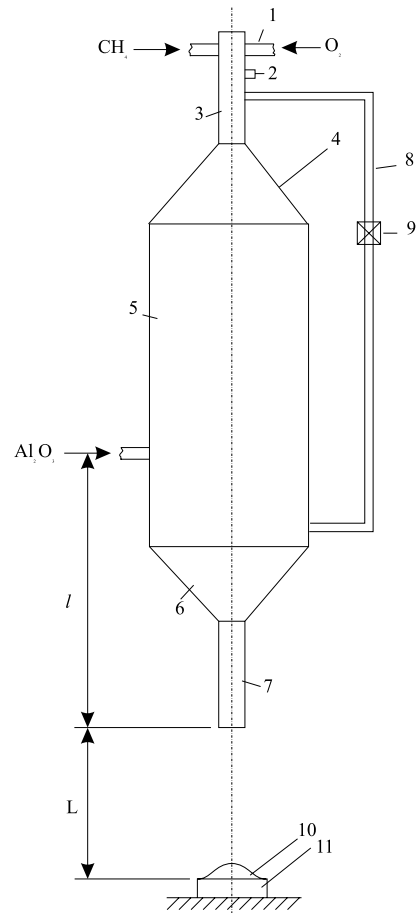


Fig. 4 Installation for Al_2O_3 spraying
 1-manifold for fuel and oxidizer,
 2-igniter, 3-prechamber,
 4-reducer, 5-main chamber,
 6-amplification unit,
 7-overcompressed detonation channel,
 8-bypass channel, 9-flow governor,
 10-spray coating, 11-substrate