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Detonation engine fed by acetylene–oxygen mixture

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ABSTRACT

The advantages of a constant volume combustion cycle as compared to constant pressure combustion in terms of thermodynamic efficiency has focused the search for advanced propulsion on detonation engines. Detonation of acetylene mixed with oxygen in various proportions is studied using mathematical modeling. Simplified kinetics of acetylene burning includes 11 reactions with 9 components. Deflagration to detonation transition (DDT) is obtained in a cylindrical tube with a section of obstacles modeling a Shchelkin spiral; the DDT takes place in this section for a wide range of initial mixture compositions. A modified ka-omega turbulence model is used to simulate flame acceleration in the Shchelkin spiral section of the system. The results of numerical simulations were compared with experiments, which had been performed in the same size detonation chamber and turbulent spiral ring section, and with theoretical data on the Chapman–Jouguet detonation parameters.

1. Introduction

One of the schemes for producing enhanced thrust at both static and dynamic conditions is pulse detonation. The thermodynamic efficiency of the Chapman–Jouguet detonation as compared to other combustion modes is due to the minimal entropy of the exhaust jet. Efforts have been made during past several decades to show that proper utilization of the operation cycle does result in improved performance. However, there are several issues in developing this technology, which represent scientific and technological challenges. The success in resolving these problems will determine the implementation of pulse detonation propulsion.

The control of detonation onset is of major importance in pulse detonating devices. The advantages of detonation over constant pressure combustion stimulated developing schemes incorporating deflagration to detonation transition (DDT) as a part of working cycle and shortening the pre-detonation length.

The probable application of these principles to create the new generation of engines put the problem of DDT on top of current research needs. Thus, the problem of DDT control in gaseous fuel–air mixtures became very acute.

This paper contains the results of theoretical and experimental investigations of deflagration to detonation transition (DDT) processes in combustible gaseous mixtures of acetylene and oxygen in different compositions. The influence of geometrical characteristics of the confinement and fuel concentration in the unburned mixture on the onset of detonation is discussed.

Detonation provides essential advantages as compared with classical combustion engine schemes from the point of view of energy conversion rate, which by three orders of magnitude surpasses the rate of energy release in classical combustion chambers. Thus the detonation regime could

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turn out to be much more effective in promoting fuel combustion in supersonic flows. Besides, one of the limitations in developing engines for supersonic flights is that of stabilization of combustion in supersonic flow, because flame propagation velocity is essentially subsonic, while detonation could be stabilized for the high Mach numbers.

The specific impulse of detonation engine is higher as compared with specific impulse of a ram jet even operating under similar conditions and having the same fuel and oxidizer average mass flow rate. The rough estimate provides the following ratio:

$$\frac{I_{PDE}}{I_{RAM}} \geq \sqrt{\gamma} = \sqrt{\frac{c_p}{c_v}}$$

Besides, the power of an engine could be increased by increasing essentially the mass flow rate of fuel and oxidizer due to the increased opportunity of the energy conversion rate. Thermodynamic efficiency of detonation mode is higher than that for deflagration, which follows from the general theory of detonation. On propagating combustion wave in a combustible mixture the final state of reaction products, as it follows from basic conservation laws, should be found on the Hugoniot curve, which has the following simplified representation:

$$\Gamma^{(1)}(p, \vartheta, p_0, \vartheta_0) = Q_0,$$

$$\Gamma^{(1)}(p, \vartheta, p_0, \vartheta_0) = e^{(1)}(p, \vartheta) - e^{(1)}(p_0, \vartheta_0) + \tfrac{1}{2}(\vartheta - \vartheta_0)(p + p_0)$$

where p is the pressure, ϑ is the specific volume, e is the specific energy, Q_0 is the specific energy released in combustion wave due to chemical reaction, superscript 1 stands for reaction products, and subscript 0 stands for unreacted mixture. At the same time, the final state of reaction products could be found on the Michelson–Rayleigh lines

$$\frac{p_1 - p_0}{\vartheta_1 - \vartheta_0} = -m^2,$$

where $m^2 = \rho_0^2 w_0^2$ is the second power of mass flow rate through a surface unit of combustion wave, and w_0 is the combustion wave propagation velocity relatively to unburned mixture.

Thus optional intersections of the Hugoniot curve and the Michelson–Rayleigh lines give us in the plane (p, ϑ) the geometrical place of all states of the medium, which could be obtained behind the combustion wave. Fig. 1 illustrates location of the Hugoniot curves and the Michelson–Rayleigh lines. In general, there could be a maximum of two intersections in the sector $p > p_0$, $\vartheta < \vartheta_0$, which correspond to compression waves. These waves have the name of strong and weak detonation, and the limiting case of those intersections coincidence gives us a tangent corresponding to the Chapman–Jouguet detonation. The two intersections in the sector $p > p_0$, $\vartheta < \vartheta_0$ correspond to deflagration mode, which is also named flame propagation.

Summarizing the advantages of detonation mode for propulsion applications as follows:

- high thermodynamic efficiency of the Chapman–Jouguet detonation as compared to other combustion modes is due to the minimal entropy of the exhaust jet,

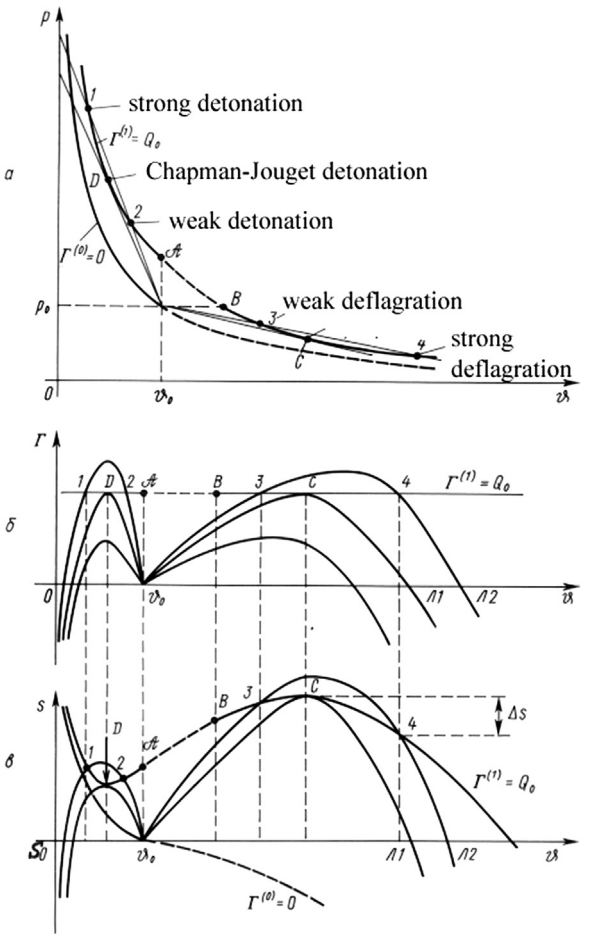

Fig. 1. (a) Hugoniot curves and Michelson–Rayleigh lines; (b) Huginiot function variation along Michelson–Rayleigh lines of different inclinations; (c) entropy variation along Hugoniot curves and Michelson–Rayleigh lines.

- CO emission reduction,
- high rate of energy conversion (10^3 times), and
- specific impulse increase.

The first studies on pulse detonation engines as reported in [1] were performed by Hoffmann in 1940, wherein mixtures of acetylene, benzyl and liquid oxygen were used. More than 10 years later Nicholls et al. investigated pulse detonation devices fed by mixtures of hydrogen and/or acetylene with oxygen [2]. The first investigations of pulse detonating devices using mixtures of hydrocarbon fuels with atmospheric air were performed in the former Soviet Union in the beginning of the 1980's [3], and demonstrated the principle possibility of creating pulse detonation engines fed by available liquid hydrocarbon fuels and atmospheric air as an oxidizer. Investigations of pulse detonation engines were continued in the 1990's of the XX-th century and beginning of the XXI-st century [4–8]. Most of the effective schemes were based on deflagration to detonation transition principles [1–4,8]. Schemes based on detonation transmission from a narrow