The problem of constructing the optimal configuration of shock and detonation waves

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Abstract. Development of technology has come to the point where new thermodynamic cycles shall be implemented in jet engines. The most promising is the thermodynamic cycle of detonation (rapid combustion). Basic concepts of shock-wave and detonation structures concepts are considered, as well as differential conditions of dynamic compatibility on shock and detonation waves. The concept of optimal shock wave and detonation structure are introduced. The task of organizing detonation combustion in preliminary generated optimal shock-wave structure is described. Basic concepts of shock adiabatic curve are given, as well as Hugoniot curve, Michelson straight lines and the model of detonation combustion of Chapman-Jouget. The concept of over-compressed and under-compressed detonation is given. Their potential application in aerospace engines is described. Formulation of task assignment of studying of structural stability of optimal shock wave and detonation structures is described. The links are provided to apply the developed mathematical tool to study the dynamics of triple configurations of shock waves in supersonic jet flows.

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Introduction

Theoretical basis of development of detonation wave generation device are considered in combustion chamber of continuous detonation engine (CDE), designed to replace conventional combustion chambers in rocket engines and gas turbine engines (GTE).

In all existing projects of detonation engines, detonation wave occurs either by triggering of a certain valve, or is formed by superposition of compression waves coming from the zone of chemical reactions. In any case, operation of such a system is completely determined by the ratio of fuel component and detonation wave propagation velocity. Fuel supply is controlled either by detonation wave itself, or by the system of valves and breakers triggered under the influence of the same wave. Such systems tend to operate at the lowest possible energy level (Helmholtz energy) resulting in the smallest possible passing frequency of detonation waves in pulse detonation engine (PDE), or the lowest possible amount of detonation combustion in rotary detonation engine (RDE) and CDE. This fact is an irremovable impediment to create efficient CDE and RDE.

Despite more than 40 years of CDE and RDE research, the results remained virtually at the level of 1964. Portion of detonation combustion does not exceed 15% of the volume of combustion chamber. The rest is a slow combustion in conditions far from optimal. As a result, specific fuel consumption per unit of draught is 30-40% higher than in conventional engine circuits. The way out of this situation is the use of optimal triple shock-wave structures for organization of continuous detonation, which allows providing a vast zone of detonation (not less than 85% of the volume against 10-15% achieved today) and “moving” the hot detonation zone from combustion chamber walls and thus reducing heat release rate of the walls by forming film cooling by unreacted fuel components.

The task is to organize stationary detonation combustion in combustion chamber in the system of optimal stationary (or cyclically moving) shock waves and finding the optimum for the given conditions. To find the required conditions, we use a newly developed theory of running optimal triple configurations of running shock waves [1-3].

Shock and detonation wave as gas-dynamic discontinuity

Gas-dynamic discontinuities (GDD) can be zero-order Φ_0 (center of expansion/compression wave, compression shock, shock wave, detonation wave and sliding surface), on which gas-dynamic parameters of the flow are discontinuous (P, v, ϑ) and of the first order, also called weak discontinuities (discontinuous characteristics, weak tangential discontinuities) Φ_1, on which first derivatives of gas dynamics variables are discontinuous. We can define features (discontinuities) Φ_i of the space of gas dynamics variables of any order.

Conditions of dynamic compatibility (CDC) in GDD Φ_0 relating flow parameters in front of the discontinuity and behind it are derived from the laws of conservation of the matter, energy flow, components of momentum flux recorded in front of the discontinuity and behind it. Intensity of discontinuity J is a parameter in these relations (most often it is defined as the ratio of pressure behind the discontinuity to the pressure in front of it).

Differential conditions of dynamic compatibility (DCDC) Φ_0 link flow nonuniformities in front of the shock and behind it:

$$N_i = c_i \sum A_{ij} N_j$$

Coefficients A_{ij}, c_i are published in the work of V.N. Uskov [4]. For the purpose of generality, $N_4=\delta/y$ ($\delta=0$ in the plane flow) and $N_5=K_\sigma$ (curvature of compression shock) are added to the equations. SWS can be studied on a plane of shock polars lnJ-β named for their characteristic form (Fig. 1) of heart-shaped curves (β is the angle of the flow turn on the shock.)

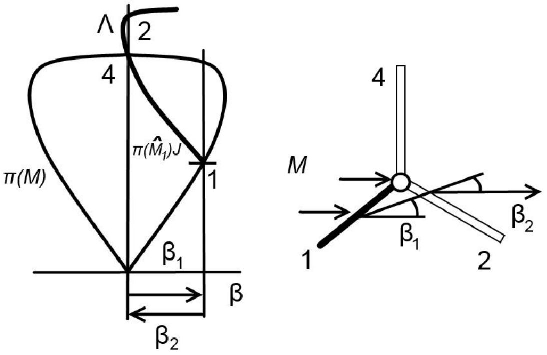

Figure 1. Heart-shaped curve and triple configuration of shock waves

Slow and fast detonation combustion

Subsonic combustion modes have the general term – deflagration. The reaction zone at layer-by-layer (slow) combustion is concentrated in a thin layer – the flame front.

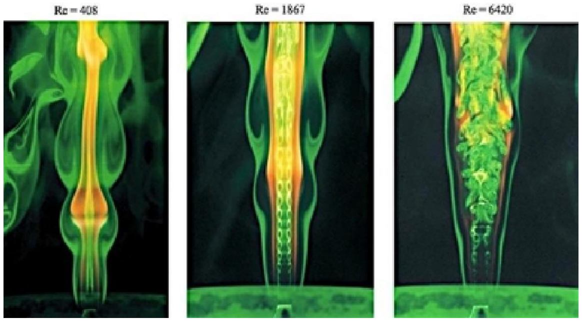

Figure 2. Laminar, transitional and turbulent combustion

Flame is the area of combustion emitting visible light. Speed of the flame front relative to the initial material is always subsonic.

In gas mixtures, the front of normal combustion (laminar flame, Fig. 2) extends at speeds from tens of centimeters to tens of meters per second. In case of turbulization of the gas flow, the rate of combustion and the effective thickness of its front increases due to convective transport of the flame by local pulsatile flows. Such combustion is called turbulent combustion (Fig. 2, right).

Combustion in the front of the shock wave is called fast or detonation combustion. And such a wave itself is a detonation wave. Detonation wave front velocity in relation to the components of fuel is supersonic.

Analysis of the modes of slow and detonation combustion by analogy with shocks and shock waves is convenient to conduct on the plane of adiabatic curves (Fig. 3) using Hugoniot curve (HC), which relates pressure and specific volume at different modes of combustion on the hypothesis that the length of the flame front (deflagration or detonation) is small and can be replaced by an infinitely thin exothermic shock.

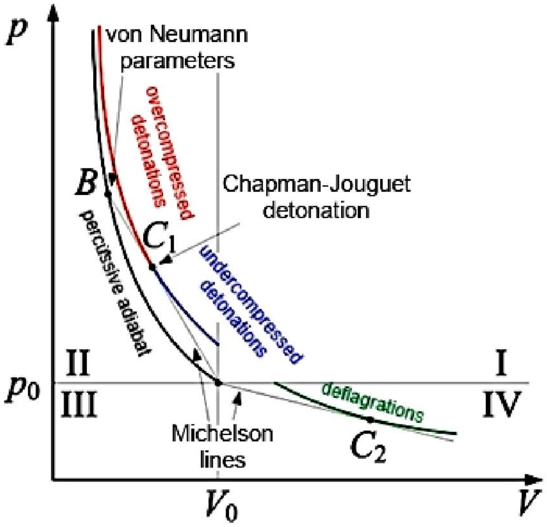

Figure 3. Shock adiabatic curve (black) and Hugoniot curve (multicolored)

Shock adiabatic curve relates the parameters of ideal gas in front of shock wave and behind it. Initial state of the substance in front of shock wave and combustion zone is characterized by parameters P_0, V_0. Straight line drawn through the point P_0, V_0 and any point on HC is called Michelson line or Rayleigh line. There are two points on HC touching Michelson lines, one on each branch, at that, the top point corresponds to the minimum wave propagation velocity for the top branch, the bottom touching point corresponds to the maximum wave velocity for the bottom branch.

Wave speed for all points of the upper branch of HC is supersonic, and for the bottom branch it is subsonic. Thus, the detonation waves only correspond to the upper branch of HC. It is called detonation adiabatic curve. The lower branch (in Figure 3 – green) corresponds to combustion waves, otherwise – deflagration.

At the touching points, the speed of transformation products in relation to the shock is equal to the local speed of sound. Steady-state detonation corresponding to the touching point of Michelson line to detonation adiabatic curve is called Chapman-Jouguet detonation. Detonations corresponding to the section of HC above Chapman-Jouguet point (red in Fig. 3) are called over-compressed, since the density of detonation products behind their front is higher than in Chapman-Jouguet point. In the section of HC below Chapman-Jouguet point (blue in Fig. 3), detonations are correspondingly called under-compressed. Chapman and Jouguet assumed that real self-sustaining detonations refer exactly to the touching point. But different types of sustainable over-compressed detonation are also known.

From the above, two practically important conclusions follow:

“Left alone” detonation wave tends to Chapman-Jouguet detonation, i.e. it is possible to obtain higher parameters of combustion products behind the detonation wave front only in a stable over-compressed detonation;

The aim of designing optimal wave structure for detonation combustion is to find the intersection of areas of existence of sustainable extreme triple shock-wave structures (SWS) and sustainable over-compressed detonations.

About the issue of designing a sustainable extreme sws

CDC and DCDC allow making a full list of possible configurations of interacting GDDs, as well as exploring the area of their existence, but they cannot tell anything about structural stability and possible modifications of SWS when changing J parameter.

Structural stability and the possible reorganizations of SWS have been the subject of research in 80-s and 90-s. Bogaevsky [5], Gurbatov and Saichev [6] (1983) made a huge contribution to the creation of complete classification of possible reorganizations of SWS. They found that starting from dimension 2, spaces of gas dynamics with even and odd dimensions have different multitudes of structurally stable SWS. It has been shown that knowing the initial position of SWS and direction of its change, it is possible to predict exactly how it will evolve, whether gas flow behind is stationary, non-stationary or oscillatory. Russian mathematicians have found all possible sequences of reorganizations of shock waves up to three-dimensional case inclusively [7]. To build optimal SWS, it is required to select structurally stable shock waves from all possible reorganizations.

In study of structural stability of SWS, it is necessary to identify degenerate critical points on the polar plane [8]. SWS corresponding to them and their reorganizations should not be implemented in practice.

Summary

Thus, the theory and mathematical tools was created sufficient to design optimal SWS in detonation combustion chamber, working both in stationary and pulsed mode.

Using the described mathematical apparatus, authors has solved the problem of finding the Mach disc in supersonic jet [9], as well as the problem of vibrational motion of triple configurations of shock waves in interaction with perpendicular barrier [10].

Conclusion

The algorithm for building optimal SWS for organization of detonation combustion might look like as follows:

Technical conditions for a particular device specify the pressure behind the detonation wave;

Solving CDC and DCDC together for triple SWS, a set of extreme SWS is found [1, 3];

The dynamics of triple SWS in the first approximation is described by the equations of one-dimensional running shock waves [2];

Using the restrictions provided by technical requirements for the device for the speed of movement and oscillation frequency of SWS, subset of optimal SWS is found that satisfies technical requirements;

For this subset, heart-shaped curves are built on the polar plane (Fig. 1) and degenerate and double critical points are found for them;

Non-degenerate critical points correspond to stable optimal SWS suitable for organization of effective detonation combustion.

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