Journal of Engineering Physics and Thermophysics, Vol. 69, No. 6, 1996

INITIATION OF DETONATION BY GASDYNAMIC METHODS

O. V. Achasov, S. A. Labuda, and
O. G. Penyaz'kov

UDC 621.373

1. Introduction. In view of recent energy problems, the need arises for a propulsion system that is less expensive but offers higher performance than the propulsion systems currently in use. The pulse detonation engine (PDE) offers a possible solution. PDEs employ an air-breathing, constant-volume process marked by high pressure and temperatures. These are conditions with higher power densities than conventional engines [1]. Therefore investigation of the different stages of the PDE working cycle, and the detonation initiation process in particular, is of great importance. Gasdynamic initiation is very attractive because it does not require additional energy sources.

In the present work some gasdynamic methods of gaseous detonation initiation in a model monocyclic detonation engine were tested. The initiation of detonation occurred by: plane shock wave focusing by reflection from concave axisymmetric or two-dimensional surfaces; interaction of supersonic jets of a combustible mixture; separate injection of acetylene and oxygen jets into the combustion chamber with supersonic mixing following; fast turbulent mixing of the hot combustion products with the detonation mixture (prechamber initiation).

2. Description of Experiments. The experiments were carried out with the use of both a shock-tube technique and detonation-chamber models. A two-diaphragm shock tube with unsteady flow expansion was used to perform axisymmetric model experiments. The inner diameter of the shock tube was 76 mm. The pressure variation in different cross sections was recorded by piezoelectric pressure gauges with a 1-mm spatial resolution. Experimental results were recorded and processed by an automatic data acquisition system that included digital oscilloscopes and a central computer.

Experiments with a two-dimensional concave reflecting surface and with interacting jets were carried out using a set of two coupled diaphragmless shock tubes with an automatic synchronization system (Fig. 1). The cross section of the rectangular shock tube was 45 × 90 mm, and the inner diameter of the circular one was 76 mm. The test section was equipped with quartz windows allowing direct photographic observation of the ignition process. A schlieren device optically aligned with a high-speed (1.3 μs/frame) photographic camera was used to visualize the process. To fix the instant at which the luminosity of the reacting gas mixture commences, the test volume was focused on a photomultiplier cathode. To eliminate light from easily excited impurities, a monochromatic interference filter was used to pass only the desired portion of the emission spectrum of the mixture. A high-pressure valve with a forced electropneumatic start (Fig. 1) was used to synchronize the start of the shock tubes with the operation of the high-speed camera and also to eliminate the influence of diaphragm breaks.

To carry out the prechamber initiation experiments rectangular (10 × 10 mm) and circular (∅ = 76 mm) detonation chambers were employed.

3. Results and Discussion.

3.1. Detonation Initiation by Focusing a Reflected Shock Wave. Our experiments determined the lowest shock-wave intensity required to initiate gaseous detonation. It is well known [2, 3] that detonation conditions are specified not only by the energy contributed to a reactive gas, but also by the power. Therefore, we took into account these two characteristics. The power and energy required for incident planar shock initiation of gaseous detonation is given by simple expressions [3]:

$$W_i = P_2 U_2 , \quad E_i = W_i \tau_i ,$$

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk, Belarus. Published in Inzhenerno-Fizicheskii Zhurnal, Vol. 69, No. 6, pp. 1035-1041, November-December, 1996. Original article submitted June 5, 1996.

1062-0125/96/6906-0807$15.00

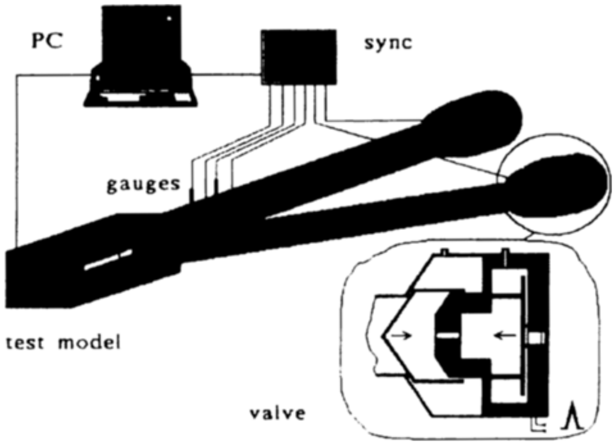


Fig. 1. Schematic of the experimental set-up.

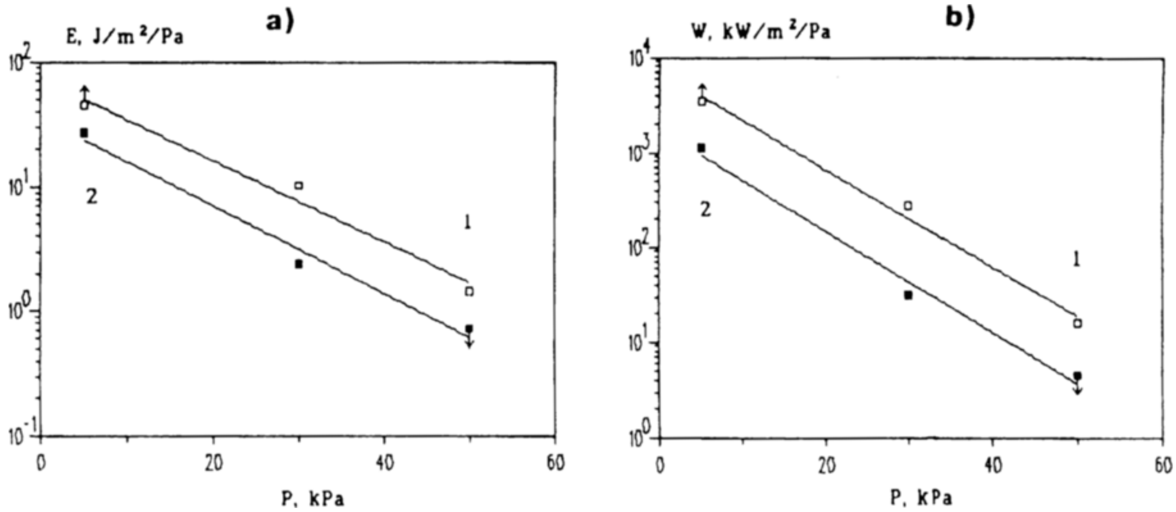


Fig. 2. Minimum energy and power of a shock-wave "detonator" in a stoichiometric hydrogen-oxygen mixture vs. initial pressure: 1) normal reflection, 2) reflection from a hemispherical cavity.

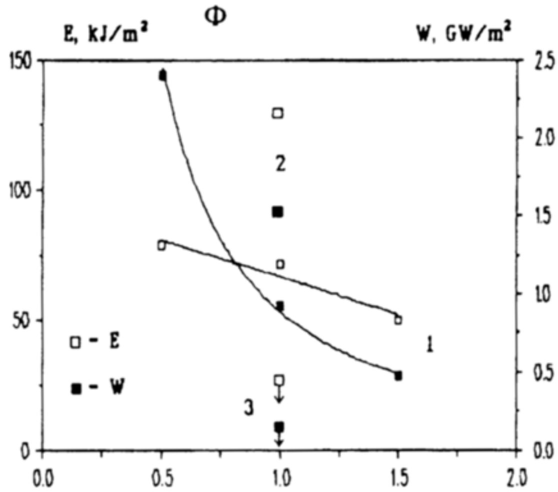
where P_2 and U_2 are the pressure and velocity at the contact surface and τ_i is the minimum time in which energy must be deposited in order to initiate a detonation. As shown in [3], this time is equal to the induction delay time corresponding to the conditions at the contact surface. In the planar case, the pressure and velocity at the contact surface are identical to those behind the shock wave and can easily be calculated.

It may readily be shown that for a shock wave that has passed through a driven section of length L_0 and was normally reflected from a plane end wall, the energy input into the reactive mixture is

$$E = P_2 U_2 \frac{L_0}{U_1} + \left(\frac{P_5 T_5}{T_1} L - P_1 L_0 \right) \frac{U_5 \tau}{L}, \quad L = L_0 \frac{U_5 (U_1 - U_2)}{U_1 (U_5 + U_2)}.$$

Here P_1 and T_1 are the initial pressure and temperature; P_5 and T_5 are the pressure and temperature behind the reflected shock wave; U_1 and U_5 are the velocity of the incident and reflected shock wave, respectively; τ is the delay time for the detonation behind the reflected shock wave. The power for this energy input is

$$W = E \Big/ \left(\frac{L_0}{U_1} + \tau \right).$$



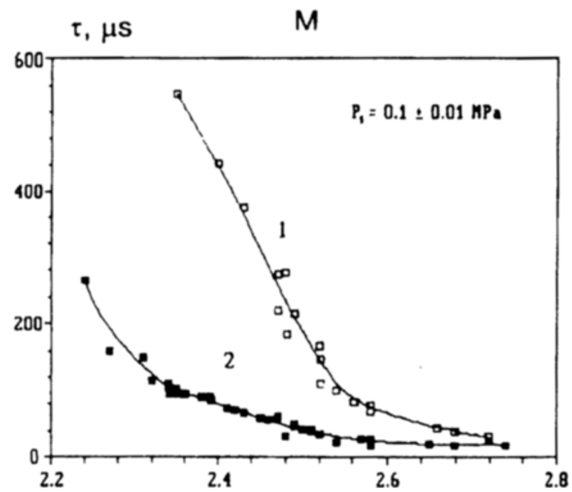


Fig. 3. Minimum energy and power of a shock-wave "detonator" for $2H_2-\Phi O_2$ (1), $2CO-O_2$ (2), and $2C_2H_2-5O_2$ (3) mixtures vs. oxidizer excess coefficient.

Fig. 4. Ignition delay time in a stoichiometric hydrogen–oxygen mixture vs. Mach number of the incident shock-wave : 1) normal reflection, 2) reflection from a concave semicylindrical (R = 22.5 mm) cavity.

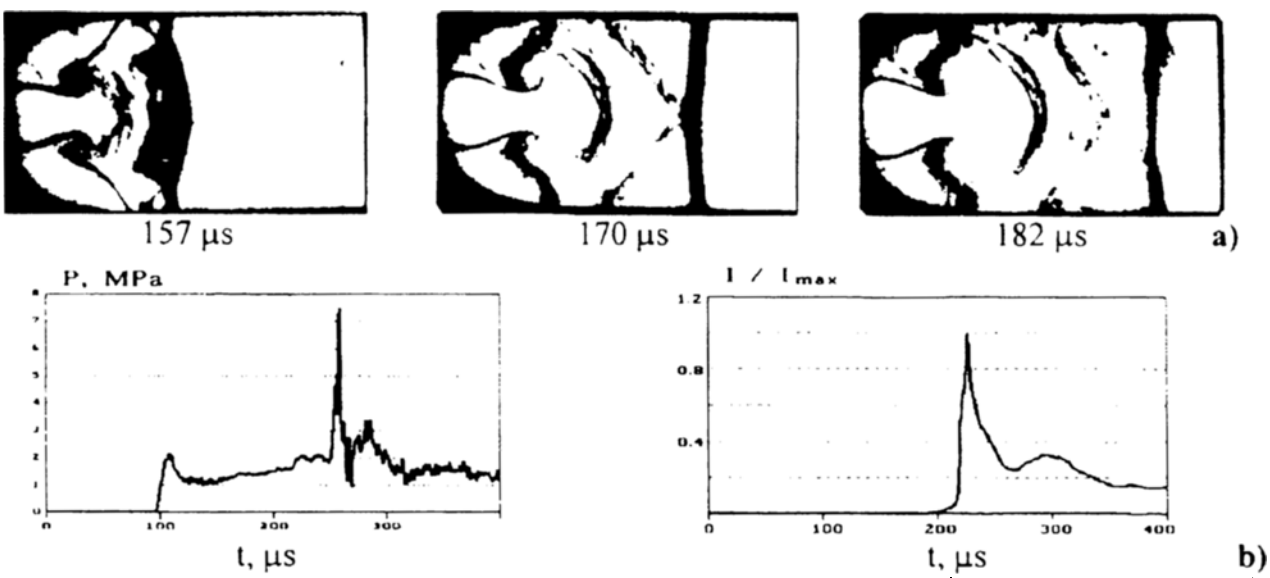


Fig. 5. Schlieren photographs (a); pressure at the bottom of a semicylindrical cavity and luminosity history (b) of shock-wave detonation initiation in a stoichiometric hydrogen–oxygen mixture at a Mach number of the incident shock wave M = 2.37. Initial pressure is 3.7 kPa.

We found that the circular reflecting surface reduces considerably both the energy and the power thresholds of detonation (Fig. 2). The observed reduction of the detonation threshold with pressure increase corresponds to results of Chan et al. [4]. We also found that the detonation threshold decreases as the oxygen concentration in the hydrogen–oxygen mixture increases (Fig. 3), which is in agreement with results of Westbrook et al. [5]. Comparative analysis of the detonation initiation conditions in stoichiometric mixtures of acetylene, hydrogen, and carbon monoxide with oxygen showed that the highest and the lowest detonation initiation thresholds correspond to the third and first mixtures, respectively (Fig. 3).

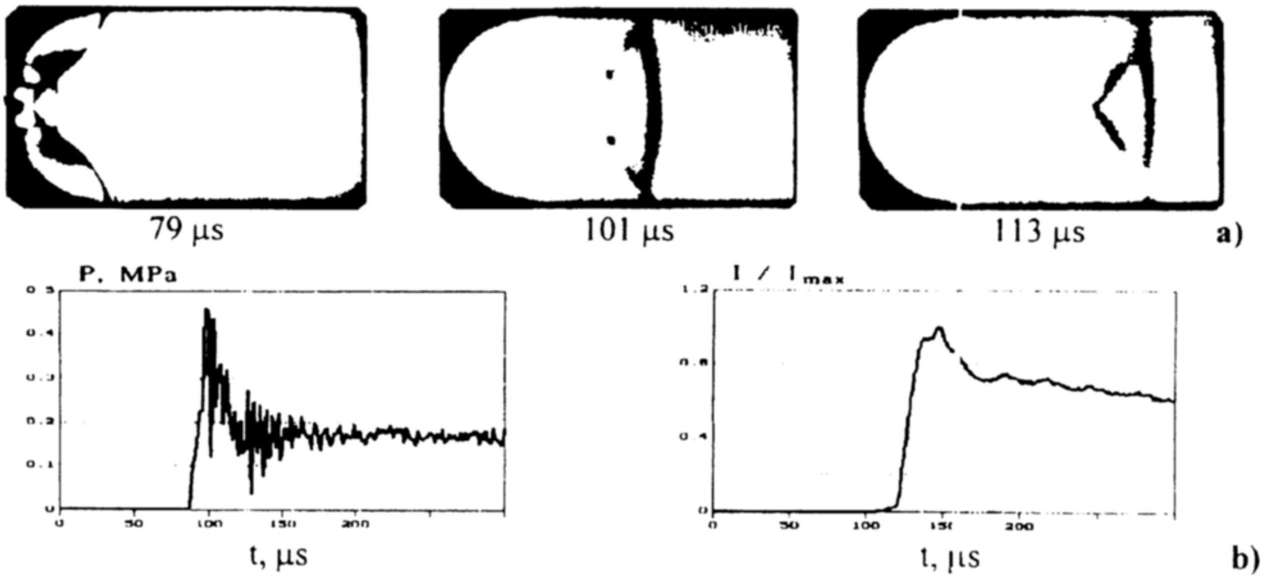


Fig. 6. The same as Fig. 5, at M = 2.65. Initial pressure is 2.8 kPa.

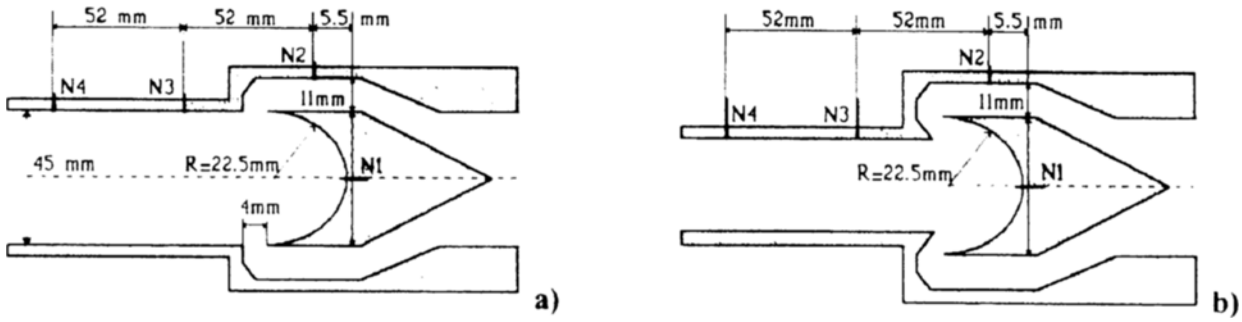


Fig. 7. Simplified sketch of test models for normal (a) and inclined (b) intraction of jets.

As follows from the plot of detonation delay (the time interval between the first and second pressure peaks recorded at the cavity bottom) as a function of the Mach number of the incident shock wave (Fig. 4), the circular reflecting surface reduces this delay significantly. It is well known [6] that a reflected shock wave from a concave wall forms a focus or a caustic at which the pressure and the temperature can be enhanced. If the incident shock is sufficiently strong, compound reflections can result in ignition of the gas mixture behind the reflected shock with detonation initiation following (Fig. 5). For an even stronger initial shock, direct initiation of detonation in the gasdynamic focal region can be achieved (Fig. 6).

3.2. Detonation Initiation by Interaction of Supersonic Jets. Experiments were performed in a 45 × 90-mm, 8-m-long, helium-driven diaphragmless shock tube. A reflected shock wave was used as the source of the jets. The jet throat (d) varied from 1 to 4 mm. The pressure variation in different cross sections (Fig. 7) was recorded by previously calibrated piezoelectric pressure gauges.

Iinteractions of jets in a semiclosed cavity have a complex gasdynamic structure in the intersection region. This process was simulated numerically using a large-particle-method (LPM) technique that achieves high resolution without nonphysical oscillations, especially at shock fronts. The two-dimensional problems were solved using both operator- and non-operator-split techniques to highlight the significant differences between these techniques when solving shock-wave problems.

Some results of numerical simulation for normally interacting air jets are shown in Fig. 8. The simulation conditions were P_5 = 0.4 MPa, P_1 = 30kPa. Here P_1 and P_5 are the initial and stagnation pressures, P_m and T_m are the highest pressure and temperature at the cavity bottom, and R and l are the cavity radius and depth,

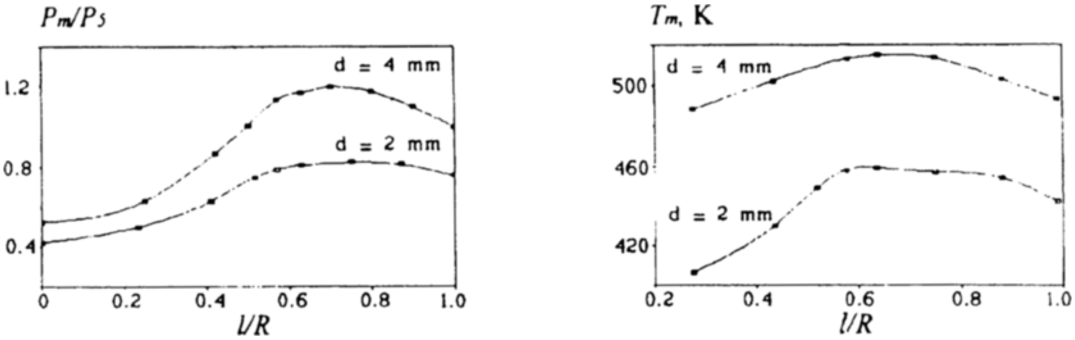


Fig. 8. Pressure and temperature amplification vs. the depth of a semicylindrical cavity.

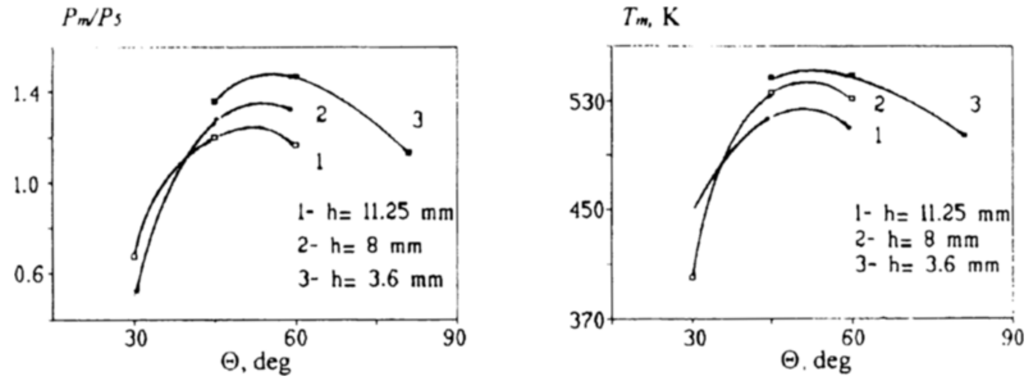


Fig. 9. Pressure and temperature amplification vs. angle of incline.

respectively. One can see that when the depth of the cavity is smaller than its radius, the temperature and the pressure at the bottom exceed the stagnation ones. When the incident jets are directed to a concave wall, the degree of focusing is higher. To produce an inclined jet an additional flat plate with a shaped side was used (Fig. 7b). As shown in Fig. 9, incline of the jets causes a 20–50% increase in P_m and T_m. Here θ and h are the angle and thickness of the additional flat plate.

First we studied the process of the interaction of nonreactive supersonic air jets in a semiclosed concave cavity and found that the interaction of two opposite gas jets injected from the lateral channel walls results in a complex gasdynamic structure (Fig. 10). A weak shock is generated and radiates out, followed by a transient starting jet exiting from the opening itself. In the case of two jets, they can intersect each other as a result of head-on collisions. At first two fronts undergo, along the line of centers, a normal interaction producing a reflected shock. At the next instant quadruple shock intersections are formed on both sides of the line of centers. When the intersection angle acquires a certain critical value, triple shock intersections set in. A turbulent vortex "bubble" heads the transient jet flow and most of the entrainment and mixing occurs in this region. When this complex gasdynamic structure collides with a circular concave wall, the reflection from the concave wall forms a focus at which the pressure and the temperature can be enhanced. We have found that the degree of focusing is higher when jets inclined to the concave wall are used.

An experiment was carried out on the direct initiation of a detonation by means of such jets. A stoichiometric mixture of hydrogen with oxygen with an initial pressure of 20 kPa was used. The interaction of normal jets ($\theta = 90^o$) produced by the reflection of a shock wave with a Mach number $M \geq 2.0$ led to the onset of detonation just in the jet reservoir, indicating that the pressure and temperature enhancement in the focus region was not high enough. The interaction of inclined jets ($\theta = 50^o$, $h = 8$ mm), on the other hand, led to the onset of detonation in the concave cavity at $M \leq 1.95$, indicating a higher degree of focusing.

3.3 Detonation Initiation by Mixing Supersonic Jets. The investigation of [7] has demonstrated that a detonation regime occurs when supersonic jets of fuel (acetylene) and oxidizer (oxygen) are mixed. Transition to

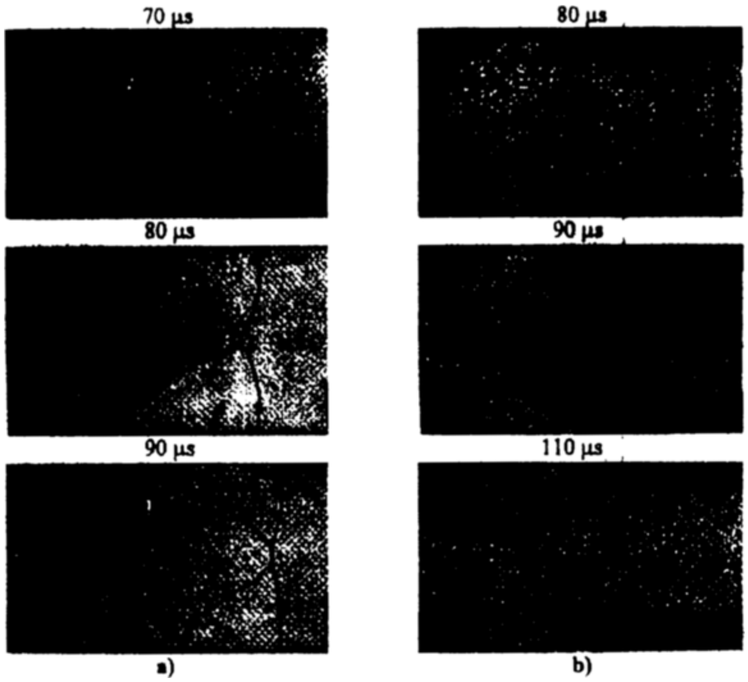


Fig. 10. Shadowgraphs of normal (a) and inclined (b) interaction of air jets. The initial pressure is 0.03 MPa, and the Mach number of the shock wave is 2.37.

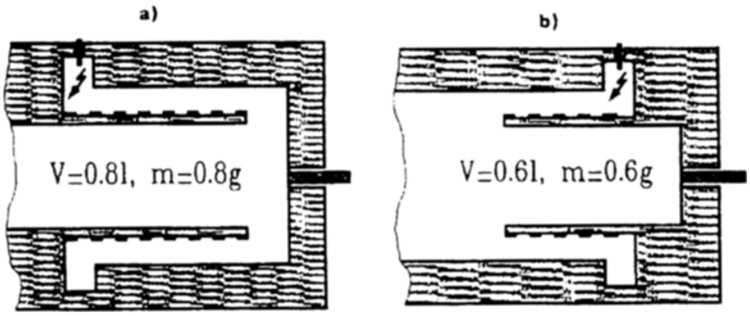


Fig. 11. Simplified sketch of test models of the direct (a) and inverse (b) scheme.

detonation takes place at the minimum distance downstream from the screen nozzle when thermal decomposition of acetylene occurs in the prechamber. At a fixed fuel stagnation temperature, the detonation regime exists only at an equivalent ratio <0.9. Preliminary thermal decomposition of acetylene in the prechamber leads to detonation at an equivalent ratio <1.1. We also observed that the use of an obstacle (diaphragm) with a transparency of 30% placed in the supersonic part of the combustion chamber allows detonation at a lower stagnation temperature.

3.4. Prechamber Initiation of Gaseous Detonations. It was demonstrated conclusively in [8] that rapid turbulent mixing of hot combustion products with reactants would produce the appearance of detonation and detonation initiated only by supersonic flame jets. An orifice obstacle reduces the transition distance and allows detonation onset at a lower pressure and higher concentration of diluter.

It was found previously [9] that detonation may be initiated by means of a quasiplanar wave flowing out of a tube of diameter d. In this case, the tube plays the part of a prechamber, being a "detonator" of the main volume. As shown by Bikovskii and Mitrofanov [10], a stable detonation wave may be obtained in a cylindrical tubular channel under certain conditions. Based on the above results, we made an attempt to initiate detonation in a model monocyclic detonation engine with a circular prechamber. We studied two types of detonation initiation,

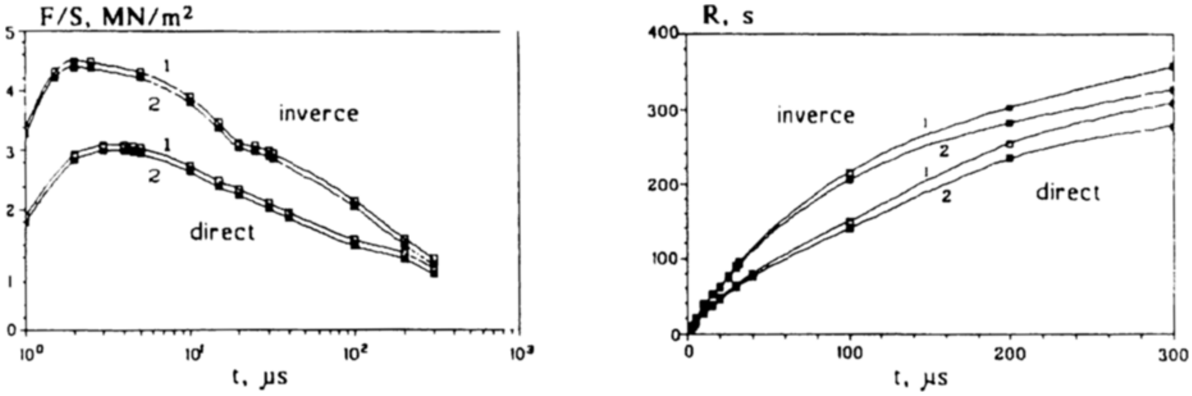


Fig. 12. Experimental results of thrust and specific-impulse measurements in vacuum (1) and at sea level (2) for a stoichiometric hydrogen–oxygen mixture. Initial pressure is 0.1 MPa.

namely, direct and inverse types (Fig. 11). The diameter of the combustion chambers and the thickness of the tubular prechambers were 76 and 10 mm in both cases. Under the inverse scheme, ignition takes place at the exit of the detonation chamber and the detonation wave propagates towards the bottom. When the direct type is used, the ignition takes place at the chamber bottom and the detonation wave propagates toward the exit of the chamber. We found that all power characteristics corresponding to the inverse scheme are higher than those of the direct scheme (Fig. 12). The maximum difference was observed at times of 50–150 μsec.

4. Conclusion. Thus, we have studied several different methods of detonation initiation, namely, plane shock wave focusing by reflection from concave axisymmetric or two-dimensional surfaces; interaction of supersonic jets of combustible mixtures; separate injection of acetylene and oxygen jets into the combustion chamber with supersonic mixing following; fast turbulent mixing of the hot combustion products with the detonation mixture (prechamber initiation). We have determined the conditions under which these methods can be realized in practice.

This work was partially supported by the Fundamental Research Fund of the Republic of Belarus, Project No. T94-055.

REFERENCES

1. A. K. Oppenheim, Introduction to Gasdynamics of Explosions, Springer-Verlag, New York (1970), p. 220.
2. G. G. Bach, R. Knystantas, and J. H. Lee, in: Thirteenth Symp. (Intern.) on Combustion, Pittsburgh (1971), pp. 1097-1110.
3. K. Kailasanath, E. S. Oran, in: Progress in Astronautics and Aeronautics. Dynamics of Shock Waves, Explosions, and Detonations (eds. J. R. Bowen, N. Manson, A. K. Oppenheim, R. I. Soloukhin), Vol. 94, New York (1984), pp. 38-54.
4. C. K. Chan, D. Lau, P. A. Thibault, and J. D. Penrose, in: Current Topics in Shock Waves, AIP Conf. Proc., New York (1990), pp. 161-166.
5. C. K. Westbrook, W. J. Pitz, and P. A. Urtiew, in: Progress in Astronautics and Aeronautics. Dynamics of Shock Waves, Explosions, and Detonations, Vol. 94, New York (1984), pp. 151-174.
6. K. Takayama, in: Proc. of the Intern. Workshop on Shock Wave Focusing, Tohoku Print, Sendai (1990), p. 228.
7. O. V. Achasov and S. A. Labuda, in: Heat/Mass Transfer – MIF-96: ASC HMTI Print (1996), pp. 105-109.
8. O. V. Achasov and O. G. Penyaz'kov, in: Heat/Mass Transfer – MIF-96: ASC HMTI Print (1996), pp. 110-114.
9. Y. B. Zeldovich, S. M. Kogarko, and N. N. Simonov, Zh. Tekh. Fiz., **56**, 8-12 (1956).
10. F. A. Bikovskii and V. V. Mitrofanov, Fiz. Goreniya Vzryva, **16**, 107-117 (1980).