ISSN 1070-3632, Russian Journal of General Chemistry, 2009, Vol. 79, No. 11, pp. 2556–2561. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © S.M. Frolov, 2009, published in Rossiiskii Khimicheskii Zhurnal, 2009, Vol. 52, No. 6, pp. 129–133.

Combustion Science and Problems of Contemporary Power Engineering

S. M. Frolov

Institute of Chemical Physics, Russian Academy of Sciences (ICP RAS), ul. Kosygina 4, Moscow, 119991 Russia
e-mail: smfrol@chph.ras.ru

Received September 9, 2008

Abstract—Nowadays fine control of physical and chemical processes at combustion and detonation of hydrocarbon fuels, aimed at obtaining certain target characteristics for power engineering applications is getting more realistic. Since control implies deep understanding of interrelations between various phenomena, the role of basic science is crucial for attacking the problem. Discussed in the paper are the latest scientific accomplishments in the field of combustion and detonation control, in particular, the possibility of controlled flameless combustion of gases, controlled combustion in porous matrices, and controlled detonations, as well as the problems of practical implementation of controlled combustion and explosion.

DOI: 10.1134/S1070363209110437

INTRODUCTION

One of the most urgent basic problems of contemporary combustion and detonation physics, directly related to power engineering, is controlling combustion of gaseous, liquid, and solid fuels and providing the highest possible completeness and thermodynamic efficiency of combustion at the lowest possible yield of hazardous substances (primarily nitrogen and carbon oxides and soot).

Combustion is an nonequilibrium physicochemical phenomenon underlain by oxidation under conditions complicated by mass and heat exchange, viz. molecular and turbulent transfer of substance and energy, heat release, and convective flows. Due to high temperatures, combustion is accompanied by various electrodynamic processes, including radiation, as well as physicochemical interactions of combustion products with the surface. Since chemical transformations is quite sensitive to temperature, this intricate phenomenon has concentration limits beyond which autonomous combustion in a flow is impossible. Near the limits combustion becomes unstable, and, therewith, certain instabilities develop, caused by different factors and mechanisms including hydrodynamic, acoustic, thermoacoustic, diffusion-heat, etc.

The paradox is that one of the most promising approaches to the above-mentioned basic problem relates to homogeneous combustion at a lower limit, specifically to combustion of mixtures where the concentration of gaseous fuel is much lower than stoichiometric; such mixtures feature unstable combustion under normal conditions. Successful solution of the problem of a stable combustion at the lower limit would provide a more complete combustion (due to the presence of a large excess of oxidizer) and ultralow yields of hazardous substances (due to the low combustion temperature). It should be emphasized that we speak here exactly about homogeneous combustion of a preprepared mixture of fuel with air. With liquid and solid fuels, such perspective implies their preliminary gasification.

One more promising approach consists in using fast combustion modes, namely detonation. Detonation is a supersonic self-sustaining combustion propagation mode in which the chemical oxidation of gaseous, liquid, or solid fuel is initiated by a powerful blast wave and take a very short time to occur (microseconds). Thermodynamically, this is the most efficient way of direct fuel combustion.

The aforesaid explains active research and development in the field of controlled detonation in power plants and technological furnaces. Cyclic combustion in running detonation waves is suggested. Successful solution of the problem of cyclic detonation

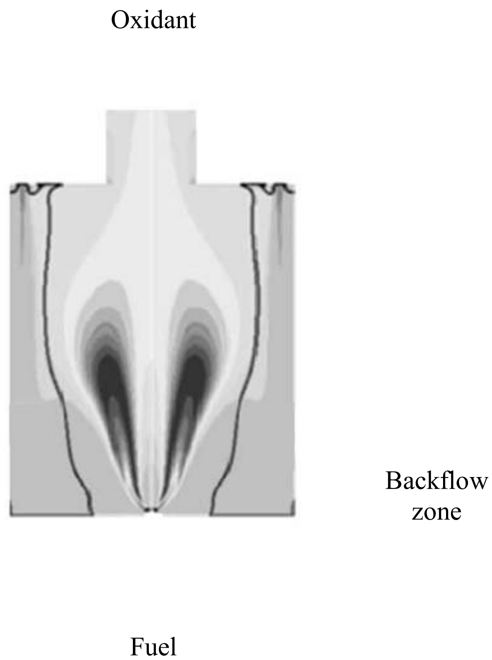

Fig. 1. Scheme of the organization of flameless combustion [2].

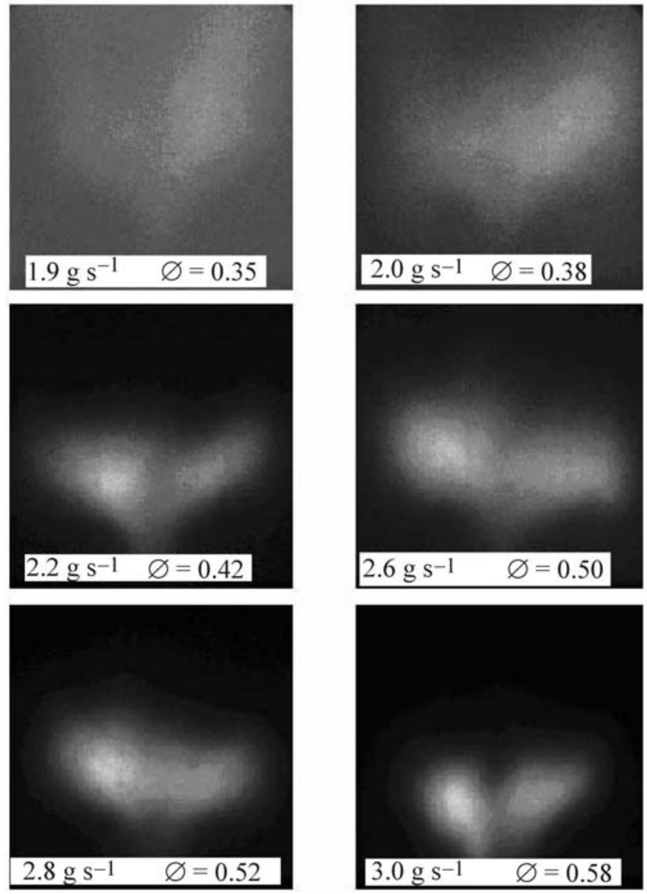

Fig. 2. OH* chemiluminescence images at 310 nm in propane–air mixtures with different fuel excess factors Φ [2].

of air mixtures of ordinary fuels (natural or associated gas, carbon particles, black oil, etc.) would allow substantial fuel savings due to enhanced thermodynamic efficiency of detonative combustion and low yields of hazardous substances (due to a very short detonation cycle).

In what follows we give a number of examples illustrative of recent advances in controlled combustion and detonation.

Flameless Combustion

One of the ways to reliably stabilizing combustion at the lower concentration limit consists in flameless combustion [1]. Flameless combustion is defined as extended (volume) combustion of fuel, involving no visible flame. For such combustion fuel and oxidizer are fed to the combustion chamber so that they very rapidly mix together before combustion initiated (Fig. 1 [2]). In other words, the components should mix together during the self-ignition induction period so that after self-ignition fuel is oxidized in the kinetically limited mode at a rate depending on the local temperature and component concentration. For reduced reaction rate recirculation of combustion products is suggested, specifically mixing with combustion products either fuel (to reduce fuel concentration) or air (to reduce oxygen concentration), or a prepared mixture of fuel with air (to reduce both component concentrations). Therewith, the degree of recirculation of combustion products define both the temperature of the mixture and the concentration of fuel and/or oxygen in it. Naturally, the better combustion products are mixed with fuel and/or oxidizer, the more homogeneous combustion occurs in the chamber and the lower is the probability of formation of local high-temperature flame centers. This combustion mode characteristically features a high degree of combustion, wide concentration range, low combustion temperature, low yields of nitrogen oxides and CO, as well as much reduced yield of CO_2, which is quite attractive in terms of power engineering applications (first of all in technological furnaces [3] and gas turbines [4]). Moreover, the flameless combustion mode is suitable for low-calorie fuels and combustible wastes.

The flameless combustion mode is illustrated in Fig. 2 by the results of experiments with propane–air mixtures with different fuel excess factors Φ [2]. In these experiments, the temperature of air fed to the combustion chamber (Fig. 1) was elevated by burning a little of propane. Therewith, the concentration of oxygen in air decreased (at the temperature of air of 800°C, the concentration of air was 14.3 vol %). The chemilumiscence images of excited hydroxyl, presented in Fig. 2, point that in very poor mixtures (Φ 0.35 and 0.38) combustion, indeed, is extended in nature. The levels of NO in combustion products under these conditions were not higher than 5 ppm.

For flameless combustion to be introduced in power engineering requires deep understanding of features of chemical oxidation of fuel in mixtures with combustion products under conditions of vigorous inhomogeneous turbulence. At present there still remain a lot of problem to be solved in this field.

Combustion in Porous Matrices

The principle of fuel combustion under “excess enthalpy” conditions, as well as certain schemes of commercial furnaces with outer heat exchanges were first suggested as far back as early 1970s [5]. Combustion of a gaseous reacting mixture in a solid porous carcass (matrix) is one of the striking examples of combustion controlled by an “inner” heat exchanger. Due to a high heat capacity of the carcass, the heating zone of the gas flame is formed under the action of additional heat flows from the hot carcass, which accelerates combustion and extends its concentration limits [6, 7]. As a result, the use of porous matrices makes it possible to burn mixtures incombustible under usual conditions, as well as mixtures much impoverished with fuel. Along with heat, the preflame zone is suggested to be exposed to chemicals via applying catalysts on the inner surface of pores. Combustion of poor mixtures in catalytic and noncatalytic porous matrices is one of promising ways to reduce hazardous emissions (first of all, nitrogen oxide) from stationary gas-turbine power plant. Another important application is destruction of hazardous wastes.

In [8] we suggested to extend the narrow flammability range by additionally supplying heat to the carcass in the heating zone of stationary flame. It should be emphasized that addition heating is supplied specifically in the flame heating zone for the most efficient use of the heat from combustion products propagating via the heat-conducting matrix. In this case, to slightly locally elevate the temperature to a level at which active preflame reactions are initiated the outer heater should be operated at the lowest power. Additional heating can be effected by means of miniheaters (Fig. 3), inserts of an electroconducting porous matrix, or microwave irradiation. In [8], combustion of methane-air mixtures was used as an

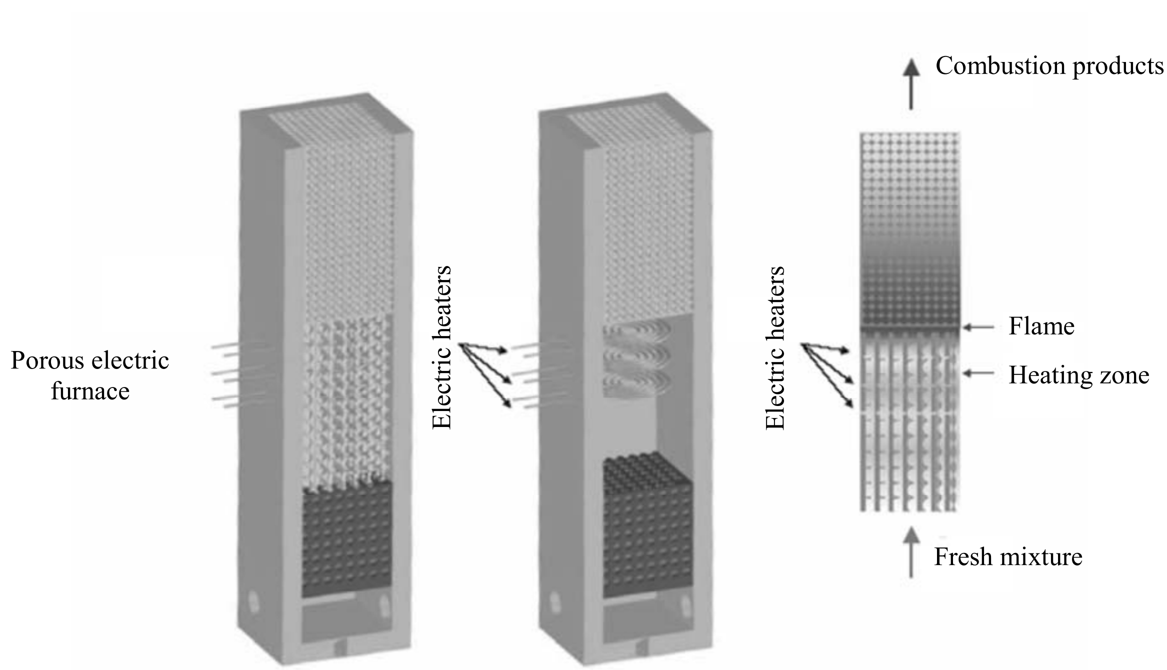

Fig. 3. Scheme of a porous electric furnace with additional heat supply to the flame heating zone by means of electric heaters.

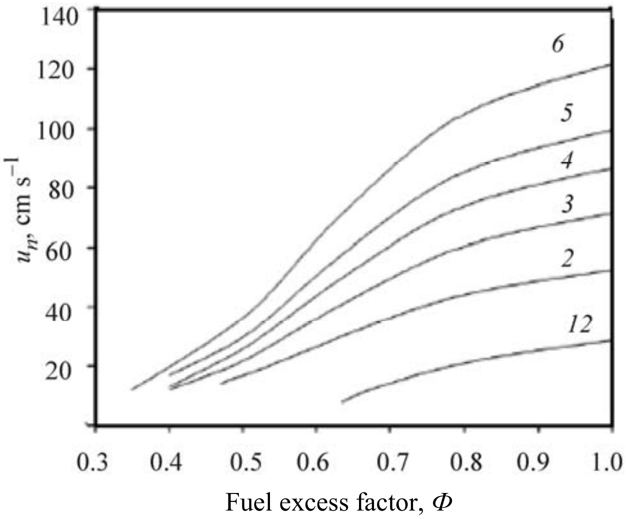

Fig. 4. Dependences of rate u_n on fuel excess dactor Φ for flame propagation in: (*1*) cold-wall hollow pipe (critical conditions: $\Phi^* = 0.635$, $u_n = 7.85$ cm s^{-1}); (*2*) porous-wall pipe without heating; (*3—6*) orous-wall pipe with a local outer heating [(*3*) $0.01\Theta_{max}$, (*4*) $0.02\Theta_{max}$, (*5*) $0.03\Theta_{max}$, (*6*) $0.05\Theta_{max}$].

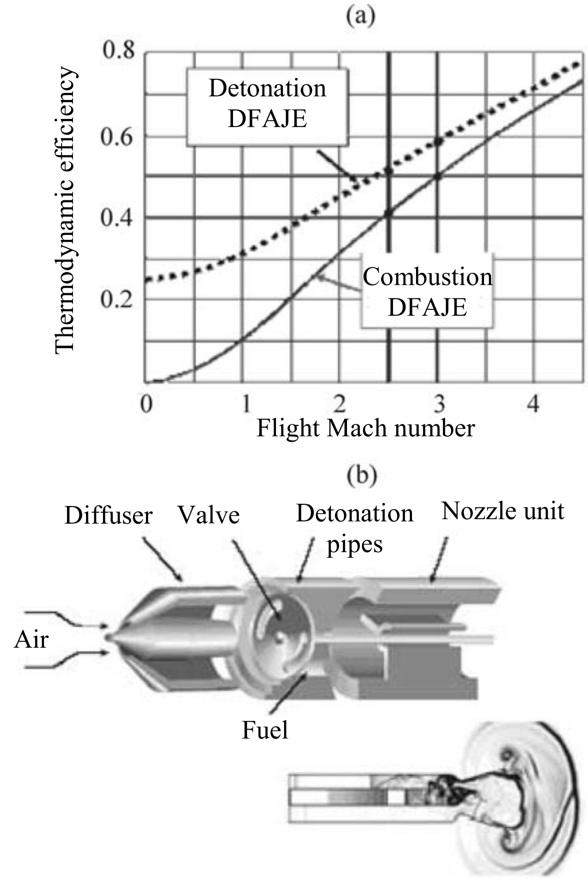

Fig. 5. (a) Advantages of detonative fuel combustion and (b) scheme of pulse detonative engine for aircrafts.

example to theoretically prove that local outer heating considerably extends the narrow flammability range, accelerates combustion, and decreases the yield of NO to an ultralow level (2–3 ppm). To extend the narrow flammability range of methane appreciably required outer heating whose power is lower (less than 3–5%) than the total heat release Θ_{max} in the laminar flame at the propagation limit without heating (Fig. 4).

A lot of problems have still to be solved before controlled combustion in porous matrices will be introduced in practice. For example, it is still unclear what is a real flame structure and what is the nature of chemical reactions in gas in the presence of quite a developed matrix surface and turbulent directed microjets. Detailed research is required to optimize the site of outer heat source in the heating zone and volume distribution of heat supply.

Detonative Combustion

The utility of detonative combustion for power engineering and jet engines was first suggested by Ya.B. Zel'dovich as far back as 1940 [9]. According to his estimates, direct-flow air jet engines (DFAJE) that exploit detonative fuel combustion should exhibit the highest thermodynamic efficiency.

From the quantitative viewpoint, the advantages of detonative combustion are best illustrated by the efficiency–aircraft flight Mach number diagram (Fig. 5a [10]). Copared to DFAJE with a normal combustion, a detonative engine is capable of providing, in an ideal case, fuel savings of up to 30% at the flight Mach number of 2.5 and up to 20% at the flight Mach number of 3, which will allow to increase either distance of flights with such engines or pay load. One more principal difference between a detonative engine and DFAJE with a normal combustion is that the former is capable to develop jet thrust at low flight speeds or even to start without assistance of overspeed vehicles.

Figure 5b shows one of the possible schemes of the organization of a detonation cycle on an example of a supersonic aircraft with a diffuser, mechanic valve, a bundle of detonation tubes, and common nozzle. Tubes are periodically filled with a fuel-air mixture. The mixture burns in running detonation waves, and hot detonation products are expelled at a high rate through the nozzle to the environment, thereby creating jet thrust. Similar schemes of the organization of detonation cycle without mechanical valves, i.e. engine contains no movable units. As seen, the design of such a pulse detonation engine (PDE) is very simple, and the thrust of this engine can be varied by varying the number of detonation tubes. Furthermore, by varying fuel feed to tubes one can control the thrust vector without pivot rudders.

Pulse detonation engines are quite attractive by their potential thrust parameters: They cover a wide range of flight speeds from 0 to Mach number 4–5, providing an almost constant specific fuel pulse at a level of 2000–2500 s (with a hydrocarbon fuel). If the flight Mach number is above 3, the pulse detonation engine bypasses in efficiency not only DFAJE, but also a turbo-jet engine.

It is important to emphasize that the creation of PDE is not limited by fundamental reasons. However, there are certain exploitation limitations: To compete successfully with existing analogs, such an engine should run on a normal aviation kerosene without active additives, use a minimum detonation ignition energy, and be compact and light. It is such exploitation requirements are considered to form the principal barrier to the creation of a practically operated engine.

The case in point is that to initiate detonation of a kerosene-air mixture in a tube by classical methods requires either huge ignition energies or very long tubes, which is inaccessible for aircraft power plants [11]. In this connection at the ICP RAS in 2002 there was set a fundamental task: to find new ways of initiating detonation, which would allow to decrease considerably the detonation ignition energy, tube length, and time of switching from combustion to detonation.

At present this task has been successfully solved by means of a whole arsenal of new combined initiation and detonation enhancement tools [12–19]. Periodic detonation of a kerosene-air mixture in at a tube length of 1.5 m after ignition with an ordinary motor spark was first obtained. Thus the detonation ignition energy could be decreased more than 10000 time, and simultaneously the tube length could decreased more than 10 times. As a result, prerequisites for initiation of practical development of a new jet propulsion system on the basis of pulse detonative combustion of kerosene were developed.

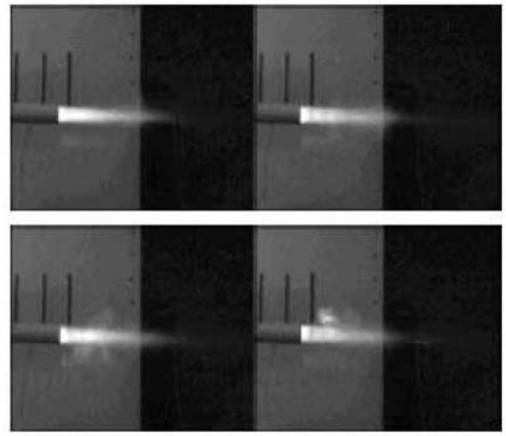

Fig. 6. Images of periodic supersonic flows of detonation products during operation of PDE demonstrator.

The above-described results were used at the ICP RAS to develop and test a demonstration model of the operating process in PDE. This is a two-circuit model: The first circuit provides a reliable cyclic detonation initiation and bypassing the detonation wave to the second-circuit pipe 52 mm in diameter and less than 2 m in total length, where detonative combustion of most fuel takes place. Figure 6 shows images of periodic supersonic jets of detonation products, obtained during operation of the demonstrative model. Thrust of the demonstrator at fairly low operating frequencies (below 10 Hz) was measured to show that the thrust is linearly related to pulse frequency, as predicted by theory. This result allows us to expect that, at a pulse frequency of up to 100 Hz, such a pipe can provide a thrust of higher 75 kg, and a bundle of 10 similar pipes can provide a thrust of higher 750 kg. For the demonstrator to be operated at higher frequencies, a group of researchers at the ICP RAS and Moscow Engineering Physics Institute (State University) [MEPI (SU)] designed a special pre-chamber igniter that provided reliable detonation initiation at a frequency of up to 60 Hz.

The above-mentioned exploitation requirements to the weight, geometric dimensions, and operating frequency of PDE relate primarily to aircraft power plants. As applied to stationary power plants, these requirements are not so important, and, therefore, we can expect an engineering breakthrough in this direction in a very near future. The most attractive line of activities is to organize cyclic detonation of mixtures of natural gas with air. At present at the ICP RAS and MEPI (SU) there is an active work on the realization of pulse detonative combustion of natural gas using new combined means for detonation initiation. Success on this way may well result in an essential saving of natural gas and enhancement of the efficiency of power-engineering equipment, in particular, power plants of gas compressor units (GCU) for cross-country gas pipelines. The latter application is of particular importance in view of the urgent demand for reduction of gas consumption by gas-transmission companies themselves. Naturally, to replace combustion liners in the gas-turbine power plants of GCU by detonation pipes will require additional investments (development of devices for attenuating pulse shock loads on turbine elements, etc.); however, the expected economic benefits of the new technology will undeniably overcover all associated costs.

Pulse detonative combustion can be used in many other applications. For example, in pulse furnaces that combine an effect of shock and an effect of a high-speed jet of hot detonation products. The above factors (pulse shock and convection heating) will be used for grinding and gasification of heavy oil and gas fractions and domestic and industrial wastes, grinding of rocks, ice, etc.

CONCLUSIONS

The rapid present development of measurement technique and electronics makes real the possibility of finely controlling physicochemical processes in flame to obtain combustion with desired characteristics. Since control implies deep understanding of cause–effect relationships between different phenomena, the role of basic science can be hardly overestimated.

There is not an uncommon recent statement that the contemporary physics of combustion and detonation has transformed from a basic science to applied focused on solving engineering problems (design of effective furnaces and combustion chambers, development of technologies of new substances and materials, etc.). Actually, over the past decades the priority in all countries, including Russia, is given to funding applied research. The physics of combustion and detonation is an interdisciplinary science which is at the interface of physics and chemistry, and, therefore, its development is especially sensitive to the administrative division into "physical," "chemicall," and other sciences and to its short-sighted given secondary role of a direction of "physical chemistry." The physics of combustion and detonation gave to mankind a unique diversity of devices and technologies that have been successfully exploited for many years, forming an illusion of a comprehensive basic knowledge of the nature of associated phenomena. Nothing to say that the state of basic knowledge in the physics of combustion and detonation, like in many other fields, is quite far from ideal, and further progress requires meticulous and systematic research.

REFERENCES

1. Wünning, J.A. and Wünning, J.G., *Progress in Energy and Combustion Sciences*, 1997, vol. 23, pp. 81–94.
2. Cornwell, M. D., Gutmark, E., Guillou, E., and Overman, N.R., *Proc. 20th ONR Propulsion Meeting*, Arlington, VA, 2007.
3. Tsuji, H., Gupta, A. K., Hasegawa, T., Katsuki, M., Kishimoto, K., and Morita, M., *High Temperature Air Combustion: From Energy Conservation to Pollution Reduction*, Boca Raton, FL: CRC, 2003.
4. Borissov, A.A., Arghode, V.K., and Gupta, A.K., *Proc. 20th ONR Propulsion Meeting, Arlington, VA, 2007.*
5. Weinberg, F.J., *Nature*, 1971, vol. 233, no. 5317, p. 239.
6. Babkin, V.S., Drobyshevich, V.I., Laevskii, Yu.M., and Popytnyakov, S.I., *Fiz. Goreniya Vzryva*, 1983, no. 2.
7. Manelis, G.B., *Priroda,* 1996, nos. 3–4, pp. 4–9.
8. Berlin, A.A., Shteinberg, A.S., Frolov, S.M., Belyaev, A.A., Posvyanskii, V.S., and Basevich, V.Ya., *Dokl. Akad. Nauk,* 2006, vol. 406, no. 6, pp. 770–775.
9. Zel'dovich, Ya.B., *Zh. Tekh. Fiz*., 1940, vol. 10, no. 17, p. 1453.
10. Frolov, S.M., *Tyazh. Mashinostr*., 2003, no. 9, p. 18.
11. Frolov, S.M., *Impul'snye detonatsionnye dvigateli* (Pulse Detonation Engines), Moscow: Torus, 2006.
12. Frolov, S.M.,, Basevich, V.Ya., Aksenov, V.S., and Polikhov, S.A., *Dokl. Akad. Nauk*, 2004, vol. 394, no. 2, p. 222.
13. Frolov, S.M., Basevich, V.Ya., Aksenov, V.S., Polikhov, S.A., *Ibid*., 2004, vol. 394, no. 4, p. 503.
14. Frolov, S.M.,, Aksenov, V.S., and Basevich, V.Ya., *Ibid.,* 2005, vol. 401, no. 2, p. 201.
15. Frolov, S.M., Aksenov, V.S., and Basevich, V.Ya., *Ibid*., 2005, vol. 402, no. 4, p. 500.
16. Frolov, S.M., Aksenov, V.S., and Basevich, V.Ya., *Ibid*., 2006, vol. 410, no. 1, p. 70.
17. Frolov, S.M., Semenov, I.V., Komissarov, P.V., Utkin, P.C., and Markov, V.V., *Ibid*., 2007, vol. 415, no. 4, p. 509.
18. Frolov, S.M., Aksenov, V.S., and Shamshin, I.O., *Ibid*., 2007, vol. 414, no. 6, p. 22.
19. Frolov, S.M. and Aksenov, V.S., *Ibid*., 2007, vol. 416, no. 3, p. 356.