JOURNAL OF PROPULSION AND POWER
Vol. 11, No. 4, July–August 1995

High-Frequency Instability of Combustion in Solid Rocket Motors

Nikolai M. Pivkin* and Nikolai M. Pelykn†
Research Institute of Polymeric Materials, Perm, Russia

Physical and chemical grounds for the unstable combustion of solid propellants in rocket motors are considered. Micro-oscillations of electric conductivity in combustion zones are measured. Nonuniform burning of propellant components and auto-oscillating gas-phase reactions are analyzed as possible reasons for the micro-oscillations. The correlation between unstable combustion of solid propellants and micro-oscillations in combustion zones is established. Possible applications of the results obtained are suggested for future motor design.

Introduction

THE term, unstable or oscillatory combustion (OC) of solid propellant in a rocket motor, denotes the combustion accompanied by regular high-frequency oscillations of pressure in a chamber that usually distort calculated pressure–time diagrams and affect the characteristics of motor operation by decreasing the specific impulse of the propellant, intensifying (up to destruction of the motor) or, vice versa, inhibiting (up to extinction) the combustion. The pressure oscillations can also intensify the burnout of thermal protection materials and nozzle liners and cause strong vibrations of chamber walls that can cause failure of the control system or lead to the disassembly of the payload.

Because OC produces extremely undesirable effects and adds complexity to the design and development of rocket systems, this phenomenon has long been the focus of attention. The solid–propellant industry experienced OC problems as early as the 1930s during the development of double-base propellants for rocket charges. At that time, the studies were totally empirical. In 1942, Russian researchers Bakaev and Galperin, suggested magnesium oxide as an effective stabilizer of combustion, and in 1948, Mudrak established the stabilizing effect of radial perforation. It was also determined that combustion stability depends on chemical composition as well as on other characteristics of burning propellant.

In the 1950s, using quick-response transducers, Margolin observed high-frequency pressure oscillations accompanying OC. He also studied the effect of acoustics on combustion processes. In 1969, Pivkin established a correlation between OC and nonuniform burning of solid–propellant components, and suggested that studies focus attention on the chemical composition of the propellant formulations susceptible to OC. Experimental studies and fundamental theoretical works of scientists from different countries have made a considerable contribution to the investigation of OC.[1]

At present, there are a few hundred publications concerned with OC of solid propellants. Most authors accept the auto-oscillating nature of the process. However, the detailed mechanism of triggering the high-frequency pressure oscillations in rocket-motor chamber remains unclear. Methods of designing propellant formulations and rocket charges that would allow one to predict and eliminate the OC in rocket motors are thus far lacking.

The occurrence of high-frequency pressure oscillations in a motor was accounted for by different mechanisms. The mechanism of thermal excitation of sound suggested by Raushenbakh[2] seems to be the most rigorous and clear. This mechanism is readily modeled in the Rijke tube under laboratory conditions. Two types of excitation of acoustic oscillations are considered:

1) Excitation by the Rayleigh principle. If heat is applied to gas at the moment of its maximum compression or is removed from gas at the moment of its maximum rarefaction, the oscillations are amplified.

2) Excitation caused by changes in gas flow velocity due to alternating drag, e.g., due to heat supply. With flow velocity increasing, the alternating component of the drag must accelerate the flow, and vice versa, as the velocity decreases, the alternating component must contribute to the flow deceleration.

The difference between the two types of heat-supply excitation of acoustic oscillations is that in the first case the oscillations appear due to phase shift between heat supply and pressure, while in the second case the oscillations are caused by a phase shift between heat supply and flow velocity.

Excitation of acoustic oscillations calls necessarily for an alternate heat supply to the operating system. This article considers possible sources of such heat supply, as applied to solid rocket motors. It is assumed that the rocket motor contains no hydrodynamic equipment able to induce acoustic oscillations in combustion chambers. The solid propellant is supposed to meet the requirements imposed on full-scale rocket charges (homogeneity and ability to burn in parallel layers).

Numerous data published by Russian and foreign authors on regular oscillations of the flow velocity of combustion products generated by burning surface and variations in the burning rate of the propellant exposed to an alternating radiant flux,[3,4] on the sensitivity of ignition and combustion processes to the action of alternating radiant flux,[3,5] and on changes in the chemical composition of propellants at the burning surface,[6–8] suggested the occurrence of oscillatory processes in the combustion zones of solid propellants. Since 1974, we have studied these processes using electric conductivity measurements. The experiments were conducted on a standard high-pressure bomb. A cylindrical sample of propellant with a channel (o.d. 36 mm, height 15 mm, channel diameter 10 mm) and 10-mm-thick steel electrodes attached to its ends is shown in Fig. 1. The shape and size of the sample as well as other experimental conditions were determined by special preliminary studies that included the following: 1) evaluation of the electric conductivities of the condensed and gas phases and estimation of near-electrode effects; 2) test for the absence of the effects caused by longitudinal, tangential, and radial acoustic oscillations of the sample channel as well as by the natural oscillations of the Helmholtz resonator; 3) search for appropriate initial temperatures and pressures for

Received Sept. 24, 1994; revision received Jan. 30, 1995; accepted for publication Feb. 6, 1995.

*Dr. Sci., Head of Division, Applied Research Institute.
†Ph.D., Head of Laboratory, Applied Research Institute.

Table 1 Amplitude-frequency characteristics of basic micro-oscillations in the combustion zones of studied propellants

Propellant	Formulation features	Pressure, MPa 1.0 f_i, kHz	1.0 A_i, mV	4.0 f_i, kHz	4.0 A_i, mV	7.0 f_i, kHz	7.0 A_i, mV
MDP-1	Contains dinitrodiethylene glycol	3.0–5.0	70–120	3.0–5.0	80–130	2.0–5.0	90–180
MDP-2	Contains nitroglycerin	3.2–3.8	150–250	4.0–5.5	170–280	4.0–5.8	200–300
MCP-1	Contains epoxy terminated rubber binder	2.5–8.0	70–140	2.5–7.5	40–140	1.0–4.0	40–120
MCP-2		5.0–20.0	30–140	2.0–7.0	20–140	1.0–3.0	60–120
MCP-3	Contains polyester	4.0–5.0	20–40	2.0–4.0	30–60	1.0–3.0	20–40
MCP-4	Contains polyfurite	4.0–8.0	40–80	1.0–5.0	20–60	8.0–15.0	10–50
MCP-5	Contains butyl rubber	8.0–10.0	30–70	6.0–7.0	20–50	14.0–16.0	10–30
MCP-6	Contains epoxy terminated rubber binder	—	—	0.7–1.4	100–220	1.2–2.3	80–180
MCP-7		—	—	1.5–4.5	60–150	2.8–4.2	40–80

Table 2 Influence of specific surface of oxidizer and certain additives on micro-oscillations of combustion zones of thiocol-based propellant at 7.0 MPA

Specific surface of oxidizer, cm^2/g	Formulation features	f_i, kHz	A_i, mV
3600	—	1.0–5.0	50–90
5500	—	3.5–6.0	50–120
5500	Oxidizer particles are coated with methyltrichlorosilane	0.5–3.0	40–100
5500	Propellant contains 2% combustion inhibitor (lithium fluoride)	0.7–1.8	30–50

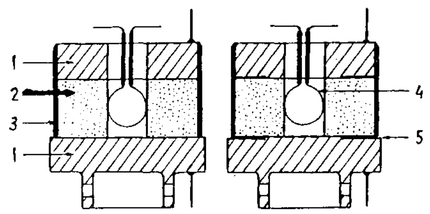

Fig. 1 Test rig: 1, electrodes; 2, tested propellant; 3, inhibiting coating; 4, wire igniter; and 5, slots.

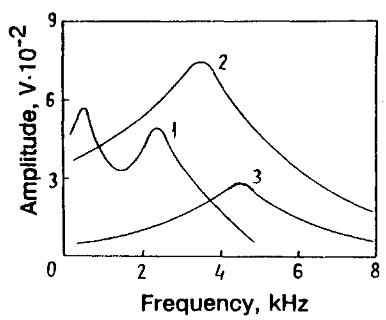

Fig. 2 Micro-oscillation spectrograms for the following propellants: 1, double-base propellant with HMX at 8 MPa; 2, composite propellant containing epoxy-terminated rubber binder at 8 MPa; and 3, composite polysufide-based propellant at 7 MPa.

each propellant formulation that would exclude self-extinction and formation of the propellant residue on electrodes; 4) simultaneous detection of variable and constant components of electric conductivity in the combustion zones and use of the latter component in the analysis of results that follow; 5) development of interpretation techniques for results obtained in different frequency regions, and choice of the optimum interval in the diagram, which would cover about 70% total time of sample combustion (the initial section of the diagram was disregarded); 6) reference test of solid samples (diameter 36 mm, inhibited lateral surface) of the propellant MDP-2 (see Table 1), which generate rather intense oscillations, and simultaneous recording of pressure oscillations by a standard pressure transducer; and 7) comparison of the oscillation frequencies of electric conductivity and pressure.

The samples were tested in nitrogen at various initial temperatures of the propellant and various pressures. Final results were obtained by averaging over 5–7 parallel experimental runs. The measurements were carried out as follows. Ignition of the sample led to formation of a space charge with oppositely charged particles in the combustion zone. As the propellant burned, the electric charge moved and a potential difference appeared between the electrodes. In oscillatory combustion, the potential alternated at the frequency of combustion oscillations. The oscillations of the positive electrode potential with respect to the ground were carried through a condenser, which was an obstacle for the constant component of electric current, then to an amplifier, after which they culminated at an oscillograph. Simultaneously, the oscillations went to a tape recorder and were then processed on a spectrum analyzer. The detection system was graduated in order to obtain the voltage amplitude A_i (mV) dependence on oscillation frequency f_i (kHz). The error was below 10% of the indication for frequency, and 50% for amplitude at frequencies of the order of 10 kHz. At higher frequencies (above 50 kHz), the error in frequency increased up to 20%.

Our studies of several types of composite and double-base propellants supported the assumption concerning the occurrence of micro-oscillations of electric conductivity in the combustion zones of every propellant. Typical spectrograms of the oscillations are shown in Fig. 2.

Some propellant formulations exhibit intense electric oscillations accompanied by insignificant pressure oscillations at the same frequency. However, for most propellants, it is impossible to detect pressure oscillations in the combustion zones by means of standard pressure transducers.

Tables 1–3 list the amplitude-frequency characteristics of micro-oscillations in the combustion zones of some nonmetallized propellants obtained from measurements of the alternating component of electric conductivity. MDP is an abbreviation for model double-base propellant and MCP means model composite propellant (oxidizer is ammonium perchlo-

Table 3 Ultrasound micro-oscillations in the combustion zones of some propellants

Propellant	Formulation features	Average pressure, MPa	f_i, kHz	A_i, mV
MDP-1	——	7	30–40	≤15
MDP-2	——	4	34–55	10–20
		7	35–60	10–20
MCP-2	Oxidizer particles are coated	4	60–90	15–30
	with methyltrichlorosilane	7	60–90	10–20
MCP-8	Contains thiocol-based binder; specific surface of oxidizer 7000 cm²/g	7	60–90	10–20
MCP-9	Contains thiocol-based binder;	4	90–100	10–20
	specific surface of oxidizer 5500 cm²/g	7	90–100	15–25

rate). It has been established that micro-oscillations in the combustion zones occur mainly at frequencies of 1–16 kHz. In some propellants, such oscillations are accompanied by ultrasound frequency oscillations of 30–250 kHz. The characters of these micro-oscillations, their frequency and amplitude, like those of sound oscillations, depend on the features of particular formulations.

The occurrence of oscillatory processes at sound and ultrasound frequencies in the combustion zones of propellants has also been confirmed to some degree by the results[9] obtained with the help of a microphone and high-sensitivity pressure gauges processed on a multichannel harmonic analyzer.

Micro-Oscillations of Electric Conductivity in Combustion Zones

Nonuniform Burning of Solid–Propellant Components

One of the considerable achievements of Russian scientists who investigated the combustion of colloid powders was the concept of nonuniform burning of powder components.

The idea of nonuniform burning of the components of nitroglycerin powders was suggested by D. Mendeleev in the early 20th century:

> It has been known that in nitroglycerin the explosion degradation rate and combustion temperature are higher than those in pyroxylin, hence, it may be assumed that in nitroglycerin powders containing a mixture of the above compounds, which undoubtedly burn in layers, the combustion starts in nitroglycerin and then extends to pyroxylin.[10]

This hypothesis, developed later by Tishunin et al.,[11] formed a basis for design of double-base propellant formulations. The propellant homogeneity is disturbed by the effect of high temperature of surrounding gases on a thin subsurface layer. The less stable and more reactive components, such as nitroglycerin and pyroxylin, dissociate to primary products (reactive groups, free radicals, etc.), while inert components, such as dibutyl phthalate and centralite, temporarily remain unchanged or, at best, change to liquid or vapor.

A moment later, the primary dissociation products of the reactive components interact exothermally to form gaseous products. The heat evolved leads to degeneration of inert components to less complex substances that react with the decomposition products of reactive components within a thin subsurface layer of the burning propellant. This mechanism has been validated by experiments with labeled atoms.[12] In particular, for a double-base propellant N, it has been shown that nitroglycerin takes an active part in the formation of both intermediate and final combustion products. Dinitrotoluene shows the least reaction under similar conditions.

The labeled atoms method was also employed in investigating the nonuniform burning of the components of a composite solid propellant.[13] The surface of extinguished composite propellant (e.g., protruding ammonium perchlorate crystals at low pressures and sunken crystals at high pressures,[14] or the presence or absence of oxidizer particles on the extinguished surface, depending on particle size and ambient pressure[6]), can sometimes be indicative of the nonuniform burning of its components.

The idea of nonuniform burning of components of composite solid propellants and of the necessity of taking it into account in analytical combustion models has also been developed by scientists in countries other than Russia.[7,8]

It should be noted that since its discovery the nonuniform burning of powder or propellant (sufficiently uniform and able to burn in layers) components is treated as the average for a large part of the surface. The assumption of nonuniform burning of components suggests the idea of oscillating conditions of surface burning for all colloid powders and composite solid propellants. During combustion of a microlayer, the propellant surface experiences small-amplitude oscillations of combustion products with fluctuating chemical composition and thermal energy. The relative regularity of the micro-oscillations depends on the individual characteristics of the thermal decomposition of certain components, the oscillation period being determined by the width of the reaction layer. As estimated by calculations, the expected frequency range is close to sonic. For instance, according to data obtained by Novozhilov's estimations[15] for a double-base propellant N at 5–10 MPa, the relaxation time of the reaction layer is 0.3–0.2 ms, which corresponds to the frequencies of 3.3–5.0 kHz.

The amplitude of micro-oscillations depends on the difference in the thermal decomposition rate of components, the thermal effect of burning of each component, propellant homogeneity, and the strength of intercomponent bonds, as well as on other factors affecting the nonuniform burning of propellant components.

It is reasonable to assume that the oscillatory processes in the combustion zones of solid propellants occurring at frequencies of 1–16 kHz are determined by the nonuniform burning of propellant components in the burning surface layer.

Auto-Oscillating Gas-Phase Reactions

It is presently known that many chemical reactions can proceed as rigorously periodic oscillatory processes.[16–19]

Unlike ordinary reactions that proceed monotonically until the reagents are exhausted or the equilibrium is established, oscillatory processes are characterized by periodic change of intermediates, in which their concentration varies as long as the stable products formed inhibit further changes.

The oscillations of chemical reactions were first discovered in the past century during studies of the oxidation of phosphorus, hydrocarbon, and carbon monoxide vapors, and investigations into the reactions at the metal-solution interface.

However, the present state of studies in the field of oscillatory chemical reactions is associated with the name, Belousov. Using a loop oscillograph, he detected changes in the

Table 4 Characteristics of oscillatory combustion in a model motor of variable length at 7–10 MPa

Charge length, mm	Calculated frequency of the first longitudinal mode	Number of tests	Propellants: MCP-6, f_i = 1.2–2.3 kHz		MCP-7, f_i = 2.8–4.2 kHz	
			$\Delta P/P_0$, %	f_i, kHz	$\Delta P/P_0$, %	f_i, kHz
90	5.8–7.1	5	0	—	0	—
140	3.7–4.2	5	0	—	4	1.6, 4.0
180	2.9–3.2	10	0	—	14	1.7, 3.3, 6.6
270	1.9–2.1	6	5	3.3–3.4	5	1.7, 3.6–4.0
360	1.4–1.5	6	83	1.2, 2.4, 3.5	0	—
450	1.1–1.2	4	24	1.0	0	—

electromotive force of the system during a reaction cycle, and revealed faster periodic processes occurring in parallel with processes observed visually.[16]

A considerable contribution to the study of the auto-oscillating chemical reactions has been made by Zhabotinskii.[17] The Belousov–Zhabotinskii reactions (accepted term for the oscillatory chemical reactions under consideration) have been studied extensively. Many experimental and theoretical studies of these processes have been carried out.[18,19] Conditions necessary for chemical oscillations as stated are as follows:

1) Chemical system can oscillate only in the absence of thermodynamic equilibrium.

2) The product of one of the reaction stages has an effect on its own formation (feedback).

3) Chemical system must have two stable states; of interest is the fact that many (maybe all) catalytic reactions can be auto-oscillating with high-frequency oscillations between two stable states.[18]

The number of studies of oscillatory reactions is increasing steadily. Of interest for the combustion theory are the oxidation reactions of carbon monoxide and hydrogen, as well as the reactions of nitrogen peroxide decomposition and nitric oxide reduction.[19] These auto-oscillating reactions take place in the gas phase in the presence of catalysts. Cupric oxide on alumina carrier, platinum, iridium, and lead were used as catalysts. Oscillations were detected by changes in flame intensity, catalyst temperature, and concentration of substances on the catalyst surface. Many authors have pointed out a dramatic increase in oscillation frequency with the temperature of the auto-oscillating reaction.

The micro-oscillations of electric conductivity at 30–250 kHz detected at high temperatures appear to be due to auto-oscillating gas-phase reactions in flame.

Correlation Between Unstable Combustion and Micro-Oscillations of Electric Conductivity

As follows from the material presented above, micro-oscillations observed in combustion zones of solid propellants vary for different propellant formulations. The term intrinsic frequency of propellant (IFP) is used.

To test the assumption concerning the correlation between micro-oscillations and OC, special experiments were carried out in a model motor with an uninhibited cylindrical charge (see Fig. 3). The charge dimensions are chosen so that the IFP is equal to the acoustic frequencies of the charge channel.

Motor tests were carried out at pressures corresponding to available IFP values. Pressure–time curves and high-frequency pressure oscillations were detected synchronously. The following characteristics were to be determined: dimensionless increment of local pressure due to unstable combustion in the form of the ratio $\Delta P/P_0$, where P_0 is the pressure in the stationary section of the pressure–time curve by the time of onset of OC; average pressure in the combustion chamber; and pressure oscillation frequency in chamber f_{oc}, characteristic of OC.

The first set of experiments, which showed a tendency toward longitudinal instability, was conducted with nonmetal-

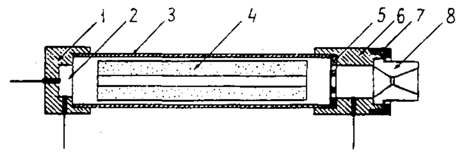

Fig. 3 Model solid rocket motor: 1, head unit with two pressure gauges; 2, cavity for igniter; 3, casing; 4, propellant; 5, grid; 6, nozzle unit with a pressure gauge; 7, coupling nut; and 8, copper or graphite nozzle.

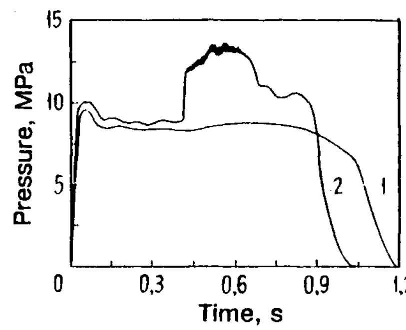

Fig. 4 Time dependence of pressure in a motor chamber under longitudinal instability of combustion for MCP-6. Charge length: 1, 270 mm, and 2, 360 mm.

lized composite propellants based on ammonium perchlorate and epoxyterminated rubber. The dimensions of the propellant charges were as follows: o.d. 45 mm, channel diameter 10 mm, and length 90, 140, 180, 270, 360, and 450 mm. The chamber of the model motor was 50 mm in diameter, with its length ranging between 105–470 mm, depending on the length of tested propellant sample. Results of the tests are given in Table 4 and Fig. 4.

It is seen from Table 4 that in a model motor of variable length the unstable combustion of propellants MCP-6 and MCP-7 shows a rather strong dependence on charge length. The oscillatory combustion manifests itself only at the charge lengths for which the IFP is close to the frequency of the first longitudinal mode of the acoustic oscillations characteristic of the charge channel. For each propellant, the maximum OC intensity corresponds to a certain length that provides the minimum difference between the IFP and acoustic frequencies. The lengths for MCP-6 and MCP-7 are 360 and 180 mm lengths, respectively. It should be noted that MCP-6 charges of 90, 140, and 180 mm lengths and MDP-7 charges of 90, 360, and 450 mm lengths exhibited only steady-state combustion.

The second set of experiments was carried out in charges of a double-base fast-burning propellant MDP-2 with an IFP equal to the acoustic frequency of tangential oscillations. The charge dimensions were as follows: o.d. 275 mm, channel diameter 45 mm, and length 1122 mm. Three experimental runs were performed. A typical pressure–time oscillogram is shown in Fig. 5.

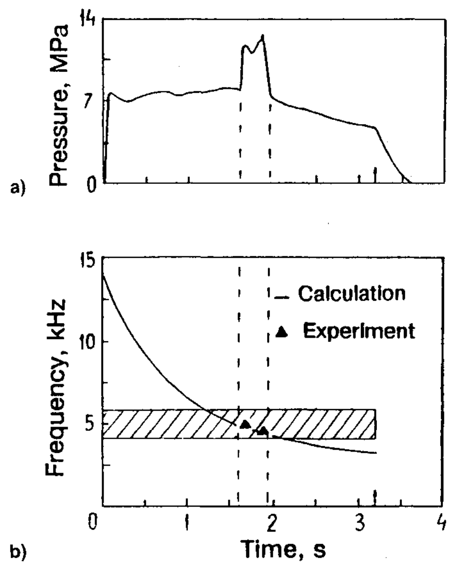

Fig. 5 Unstable combustion at equal intrinsic and acoustic frequencies: a) time dependence of pressure and b) change in frequency of first tangential mode of charge channel cavity relative to intrinsic frequencies of propellant during combustion. Shaded area, IFP at 7 MPa.

The results suggest that the coincidence of the intrinsic frequency of MCP-2 with the first mode of acoustic tangential oscillations causes the occurrence of OC in the motor under study.

The influence of ultrasound oscillations on the excitation of OC in a model motor was studied for polysulfide propellants. The dimensions of the propellant charges were: o.d. 45 mm; channel diameter 10 mm; length 180 mm. The i.d. of the chamber was 50 mm, and the chamber length was 200 mm.

Nine experimental runs in the motor chamber at 7 MPa were performed for each of the following formulations: MCP-8, MCP-9, and MCP-9 doped with 2% lithium fluoride. MCP-8 and MCP-9 charges exhibited OC at $\Delta P/P_0 \sim 25–40\%$ and tangential oscillations of pressure at a frequency of 26–57 kHz. The MCP-9 propellant containing 2% lithium fluoride, which shows no micro-oscillations, burned steadily under the same experimental conditions. It can be seen from Table 3 that the ultrasound oscillations for MCP-8 and MCP-9 are close or multiple to tangential oscillations (at the given charge dimensions).

The experiments support the assumption concerning the direct dependence of unstable combustion of solid propellant on regular micro-oscillations in the combustion zones of the propellant. At favorable conditions (coincidence or multiplicity of frequencies), the combustion zones excite acoustic oscillations inside the motor chamber. The excitation mechanism appears to be similar to that described by Raushenbakh.[2]

Methods for Attenuation and Elimination of Unstable Combustion in Rocket Motors

Optimization of Propellant Formulations

The undesirable effects of oscillatory combustion in motors have motivated search for methods and means for elimination of the unstable regime. The evolutionary history of solid propellants reflects to some extent the history of investigation of unstable combustion and methods for its removal.

In practical terms, the problem of attenuation of pressure oscillations in motors proved to be extremely difficult. The dependence of oscillations on many factors has led to the development of two basic approaches to the problem: one implies variations in propellant formulations, the other assumes design changes.

The most popular method involves the inclusion of refractory additives and various heat-producing metals in propellant formulations. For instance, the addition of 2–3% magnesium oxide to double-base propellant formulations stabilizes the combustion of these propellants. A similar effect is observed when composite propellants are doped with 5% (but no less) powdered aluminum. The fine-grained aluminum oxide formed during combustion first of all attenuates the tangential (high-frequency) oscillations. However, at oscillation frequencies below 1 kHz, this method is inefficient since (according to acoustics laws) fine-grained aluminum oxide cannot damp out low-frequency oscillations. Our investigations extend the number of formula-changing techniques for attenuation and elimination of OC in rocket motors. Appropriate choice of binder and oxidizer grain size, oxidizer modification by coating the crystals with specific substances, variation of manufacturing conditions, etc., allow one to considerably minimize the micro-oscillation amplitude in the combustion zones or mismatch IFP and acoustic frequencies. For example, one of the propellant formulations tested experienced OC at 3.6 kHz (the first tangential mode for the charge channel). The initial composition of the composite propellant exhibited IFP within 2.1–4.6 kHz. A change in the oxidizer grain size gave the IFP variation within 4.3–5.7 kHz and steady-state combustion. Unfortunately, in some cases it is impossible to make desirable changes in propellant formula because of technological difficulties.

Changes in Motor Construction

The unstable combustion of solid propellant depends essentially on the construction of the rocket motor. Whenever possible, this fact is taken into account in developing new systems.

The physical meaning denotes a change in the acoustic oscillation energy of combustion products due to enhancing or attenuating the oscillations in different parts of the motor or propellant charge. Various devices such as nonflammable rods, round partitions with holes, Helmholtz resonators, etc., can be inserted in the charge channel or mounted in the front section of the motor. Sometimes, the desired effect is achieved through radial perforation of the lateral surface of the tube-shaped charge.

The excitation of longitudinal modes of OC depends on the ratio of the cross section areas of motor chamber or charge channel and nozzle throat. The greater the ratio, the more intense the OC. The angle of convergence of the convergent section of the nozzle also has a noticeable effect on OC excitation. In particular, a change of convergence angle from 90 to 270 deg significantly enhances the OC in real motors. Counterflow motors are favorably disposed to OC. To eliminate the OC effect, a perforated antiresonance partition made of graphite or other refractory material is used. It has been found empirically that the overall perforation area must cover 12–25% of the overall partition area. The partition is mounted at the point at which the flows meet.

Acoustic absorbers of oscillation energy based on refractory porous materials are interesting from the viewpoint of attenuation of high-frequency oscillations in motors. The materials are produced by a powder metallurgy technique, and have a three-dimensional structure with micropores and cells. The frame metals are steel, tungsten, nickel, and various pseudoalloys. Damping effects occur due to viscous friction of gas in the frame, transformation of kinetic energy of oscillations to the thermal one, and dissipation of thermal energy according to transient heat exchange laws. Disks up to 20 mm thick covering the surface of the front closure (on the inside of motor) provide damping of longitudinal and essential attenuation of tangential modes of OC. The acoustic absorbers can be of various shapes and sizes.

Conclusions

Experimental measurements have shown that the combustion zones of solid propellants experience micro-oscillations of electric conductivity of combustion products and gas phase pressure at frequencies of 1–16 kHz. Some propellants also exhibit ultrasound oscillations at 30–250 kHz.

A possible reason for the sound-frequency micro-oscillations (1–16 kHz) is the nonuniform burning of propellant components. The ultrasound oscillations (30–250 kHz) may be accounted for by auto-oscillating chemical reactions that take place in the gas phase. In any case, the oscillations under discussion are determined by the chemical nature of propellant and are the individual characteristics (termed intrinsic frequencies) of propellant.

Special experiments in a model motor have confirmed the direct correlation of the oscillatory combustion of solid propellants with the micro-oscillations of electric conductivity in the combustion zones. Despite their small amplitude, micro-oscillations under favorable resonance conditions seem to excite acoustic oscillations in the combustion chamber and lead to unstable (oscillatory) combustion of the whole charge. Presumably, the excitation follows the mechanism of thermal excitation of sound studied by Raushenbakh.

Modern methods of eliminating oscillatory combustion are based on two basic approaches that involve optimization of propellant formula and use of special design elements in a motor or propellant charge. The study of micro-oscillations and their effect on the stability of charge operation resulted essentially in extension of the potential of the first approach, based on variations in the chemical nature of propellant components, and binder, oxidizer dispersity, the application of special coatings to crystals, and addition of combustion catalysts or inhibitors to propellant formulations.

Present understanding of the oscillatory combustion of solid propellants allows one to treat this process as controllable and to propose its application as a positive influence on the national economy.[20]

References

[1]De Luca, L., Price, E. W., and Summerfield, M. (eds.), *Nonsteady Burning and Combustion Stability of Solid Propellants*, Vol. 143, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1992.

[2]Raushenbakh, B. V., *Oscillatory Combustion*, Fiziko–Matematicheskaya Literatura, Moscow, 1961.

[3]Mihlfeith, S. M., Baer, A. D., and Ryan, N. W., "Propellant Combustion Instability as Measured by Combustion Recoil," *AIAA Journal*, Vol. 10, No. 10, 1972, pp. 1280–1285.

[4]Simonenko, V. G., Zarko, V. E., and Kutsenogii, K. P., "Experimental Study of Self-Sustained and Constrained Oscillations of Powder Burning Rate," *Fizika Gorenia i Vzryva*, Vol. 16, No. 3, 1980, pp. 30–68.

[5]Kumagai, H., "On the Ignition of Solid Propellant Subjected to Periodic Heating with Emphasis on Selective Frequency Sensitivity," *Proceedings of the Fifth International Symposium on Space Technology and Science* (Tokyo, Japan), 1963, pp. 65–72.

[6]Ilyukhin, V. S., Margolin, A. D., Mysov, V. G., and Novikov, S. S., "The Role of Heterogeneity of Composite Propellant in Oscillatory Combustion," *Fizika Gorenia i Vzryva*, Vol. 11, No. 3, 1975, pp. 498–501.

[7]Price, E. V., "Relevance of Analytical Models for Perturbation of Combustion of Solid Propellants," *AIAA Journal*, Vol. 7, No. 1, 1969, pp. 153, 154.

[8]Cohen, N. S., "Response Function Theories that Account for Size Distribution Effects—A Review," *AIAA Journal*, Vol. 19, No. 7, 1981, pp. 907–912.

[9]Bell, W. A., Craid, J. I., and Strahle, W. C., "Study of Unsteady Combustion of Heterogeneous Solid Propellant by Analysis of Acoustic Emission," AIAA Paper 77-15, Jan. 1977.

[10]Mendeleev, D. I., *Collected Works*, Vol. 9, USSR Academy of Sciences, Moscow, 1949, pp. 43–45.

[11]Tishunin, I. V., private communication, Moscow, 1954.

[12]Feliksov, G. I., private communication, Moscow, 1961.

[13]Andreev, B. G., private communication, Moscow, 1972.

[14]Beckstead, M. W., Derr R. L., and Price C. F., "A Model of Composite Solid-Propellant Combustion Based on Multiple Flames," *AIAA Journal*, Vol. 8, No. 12, 1970, pp. 2200–2207.

[15]Novozhilov, B. V., *Transient Combustion of Solid Propellants*, Nauka, Moscow, 1973.

[16]Belousov, B. P., "Periodic Reaction and Its Mechanism," *Khimiya i Zhizn'*, No. 7, 1982, pp. 65–70.

[17]Zhabotinskii, A. M., *Self-Sustaining Oscillations of Concentration*, Nauka, Moscow, 1974.

[18]Epstein, I. R., Kustin, K., De Kepper, P., and Orban, K., "Oscillatory Chemical Reaction Reactions," *Scientific American*, Vol. 246, No. 2, 1982.

[19]Garel, D., and Garel, O., *Oscillations in Chemical Reactions*, Springer–Verlag, New York, 1983.

[20]Zhukov, B. P., "The Use of Powder in National Economy," *Zhurnal Vsesoiusnogo Khimicheskogo Obschestva imeni D.I. Mendeleeva (Journal of Mendeleev All-Union Chemical Society)*, Vol. 36, No. 1, 1991, pp. 84–93.