JOURNAL OF PROPULSION AND POWER
Vol. 15, No. 6, November–December 1999

Temperature and Pressure Sensitivities of Burning Wave Parameters of Nitramine-Containing Propellants and HMX

A. A. Zenin,* S. V. Finjakov,† V. M. Puchkov,† and N. G. Ibragimov†
Russian Academy of Sciences, 117977 Moscow, Russia

Burning rate and burning surface temperatures have been obtained experimentally for modern double-base propellants containing nitramine additives and for HMX. Temperature sensitivities of burning wave parameters were estimated from the experimental data measured at pressures of 20 and 100 atm and at sample temperatures of − 80, +20, +100°C. Evaluation of standard deviations of the estimations shows that smoothing procedures for dependencies of burning wave parameters on pressure and temperature are necessary to obtain correct values of the sensitivities. Calculations of the criteria for stable combustion show that Novozhilov's [Novozhilov, B. V., "Nonstationary Combustion of Solid Rocket Fuels," Nauka, Moscow, 1973 (Translation AFSC FTD-MD-24-317-74) (in Russian) and Novozhilov, B. V., "Theory of Nonsteady Burning and Combustion Stability of Solid Propellants by Zel'dovich–Novozhilov Method," ***Nonsteady Burning and Combustion Stability of Solid Propellants*****, edited by L. DeLuca, E. W. Price, and M. Summerfield, Vol. 143, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1992, Chap. 15, pp. 601–641] criterion correctly predicts regimes of stable combustion of the propellants and HMX. An analysis of burned surface irregularities of the propellants confirms one-dimensional character of the combustion under the investigated conditions.**

Nomenclature

E	= activation energy of solid gasification, kcal/mol
k	= Zeldovich criterion of stable combustion, dimensionless
k_{01}	= pre-exponent factor, 1/s
k^*	= Novozhilov criterion of stable combustion, dimensionless
l	= thickness of heat layer in solid, μm
m	= mass burning rate, g/cm^2 s
$\boldsymbol{p}$	= pressure, atm
Q	= heat release in solid, cal/g
Q^*	= maximum of heat release in solid, cal/g
$\Re$	= gas constant, cal/mol K
$\boldsymbol{r}$	= temperature sensitivity of burning surface temperature, dimensionless
r_b	= linear burning rate, cm/s
T_s	= burning surface temperature, °C
T_0	= sample temperature (initial sample temperature), °C
$x^{\sim}$	= size of burned surface irregularity, μm
β	= temperature sensitivity of mass burning rate, %/K
Δx	= relative standard deviation of x ($\Delta x = \delta x/x$), dimensionless
δx	= absolute standard deviation of x
λ	= coefficient of propellant heat conductivity, cal/cm s K
$\boldsymbol{\nu}$	= pressure sensitivity of mass burning rate, dimensionless
ρ	= propellant density, g/cm^3
$\Psi_l(x^{\sim})$	= probability of encountering an irregularity of size $x^{\sim}$ on length l, dimensionless

Received 4 February 1998; revision received 7 August 1998; accepted for publication 8 August 1998.

*Professor, Head of Laboratory, Department of Solid Combustion, Semenov Institute of Chemical Physics.

†Senior Research Associate, Department of Solid Combustion, Semenov Institute of Chemical Physics.

Introduction

TEMPERATURE and pressure sensitivities of burning wave parameters are very important characteristics of solid propellant combustion. The characteristics can show the many peculiarities of combustion mechanisms, and they can be used for predictions of different phenomena of solid combustion. In particular, the characteristics that have been obtained at stable combustion play a significant role for calculations of nonsteady and pulsatory combustion of solid propellants.

There have been numerous experimental and theoretical works devoted to the problem of burning-wave parameter sensitivities. Cohen and Flanigan[1] in a review paper on the burning rate temperature sensitivity (BRTS) discuss experimental data and their interpretations. References 2 and 3 contain discussions on dependencies on pressure for BRTS of HMX and modified double-base propellants. Kubota[4] gives a set of experimental data and their interpretations for different combustible solids: ammonium perchlorate composite mixtures, double-base propellants, nitramine composite modified (nitramine-containing) double-base propellants, and nitramine and azide composite mixtures. Cauty et al.[5] present an ultrasonic method and some results on determination of solid propellant BRTS and give a comparison with the results obtained by other methods. A review of existing results on BRTS of monopropellants, AP, AND, HMX, RDX, CL-20, and HNF, is found in Ref. 6. The conclusion of the work specifies, in particular, that BRTS increases if sample temperature increases. References 7 and 8 contain experimental data and their interpretation for temperature sensitivities of burning rate β and burning surface temperature $\boldsymbol{r}$ of modern double-base propellants including nitramine-containing propellants. Theoretical expressions were obtained in Refs. 7 and 8 for β and $\boldsymbol{r}$ on the basis of the first unified dependency connecting burning rate and burning surface temperature. These expressions are valid in a very wide region of pressures, and they include parameters that have been measured experimentally: burning surface temperature, burning rate, propellant caloric power, and activation energy of solid gasification. Expressions were obtained that demonstrate the unified dependencies for $\beta(\boldsymbol{p})$ and $\boldsymbol{r}(\boldsymbol{p})$. It was found also that estimated values β and $\boldsymbol{r}$ coincide with experimental data for simple double-base propellants. The expressions show that β decreases when surface temperature, pressure, and heat release in a solid increase and that $\boldsymbol{r}$ decreases when pressure and heat release in a solid increase and surface temperature decreases. These tendencies are valid for all types of propellants. However, there is some disagreement between the quantitative values of β calculated by the expressions and the experimentally obtained values of β for nitramine-containing double-base propellants.

The main problem in this field of combustion investigations is a lack of experimental data for β and $\boldsymbol{r}$ for modern propellants. The work presented in this paper is aimed to fill the gap. The work presents experimental data, mass burning rate, and burning surface temperatures for four nitramine-containing propellants that were investigated at different pressures and sample initial temperatures T_0. Processing of the experimental data allows sensitivities of burning-wave parameters and criteria of stable combustion to be obtained and conclusions about the validity of the one-dimensional approach to complex propellant combustion analysis to be made.

Experimental Approach and Results of Measurements

This paper has four tasks: 1) to obtain by experiment the mass burning rates and burning surface temperatures for different regimes of nitramine-containing propellant combustion, 2) to evaluate differential characteristics of combustion waves, pressure and temperature sensitivities from the experimental data by the improved evaluation procedure, 3) to use the sensitivities to estimate the criteria of stable combustion, and 4) to check the validity of stable combustion predictions by the criteria.

Microthermocouple methods were used to obtain temperature distributions (temperature profiles) across the propellant combustion waves and to measure burning surface temperatures.[9,10] The temperature profiles were obtained by microthermocouples imbedded into solid by acetone. Thermocouples went through the combustion waves, when the waves propagated through the solid samples, and registered temperature profiles. The ribbon U-shaped microthermocouples of alloys W + 5%Re/W + 20%Re, 3.5–7 μm thick were used. Every sample had 2–3 thermocouples inside placed one above the other. Distances between junctions were 2–4 mm. The samples burned in a constant pressure bomb in an atmosphere of nitrogen at pressures of 20 and 100 atm and at $T_0 = -80$, $+20$, and $+100$°C. The ignition was performed by heated nickel–chromium wire. In experiments at elevated and negative T_0, the samples were placed into a small thermostat that heated or cooled the samples inside the bomb. The burning rate was measured by the time delay between the thermocouple signals, by the registrations of the time of pressure increase in the bomb during the sample combustion, and by optical registration of the burning-wave movement. Thermocouple signals were registered by amplifier and oscillograph. The burning surface temperatures were determined by establishing the locations of slope breaks on temperature profiles registered by thermocouples. The phenomenon of the slope break is caused by the delay of the temperature rise on the curve registrated by the thermocouple when the thermocouple goes through the burning surface. At that moment the intensity of heat exchange between the thermocouple and environment decreases due to replacing the contact heat exchange in the solid by the convective heat exchange in gas. The burning surface temperature at 20 atm and normal T_0 also were measured by the thermocouple pressed to the burning surface during the sample combustion.

Modern complex propellants, as is well known, may contain different high-energy nitramines that are imbedded in a double-base binder system. These nitramines, such as HMX, have many advantages.[11] Four nitramine-containing double-base propellants were selected for this investigation, labeled A–D. Table 1 shows the compositions of the propellants. Basic propellant A has 55% nitrocellulose, 20% nitroglycerine, 20% nitrosoamine (1,4,5,8–tetranitrosotetrasamine) and 2% catalyst (Ni); all percentages are by weight. Density of the propellants is equal to $\rho = 1.6$ g/cm^3. Composition of the remaining propellants was chosen to check the influence of adding HMX (amount and particle size) and the influence of the catalyst (very small Ni particles). Propellant B has a 10% addition of HMX with relatively large particles, 40 μm. Propellant C has the same composition as propellant B but without the catalyst. Propellant D has the same content of HMX as propellant C, however, with small particle sizes (10 μm).

Table 2 shows results of measurements of mass burning rate m and burning surface temperature T_s. It can be seen that increasing m always leads to increasing T_s. This implies that the measured values m and T_s can meet the unified dependency $m(T_s)$ obtained for double-base propellants.[8,12,13] Indeed, Fig. 1 shows that practically all of the points measured for the chosen propellants can be treated as points belonging to the unified dependency $m(T_s)$. If so, it is reasonable to take for calculations corrected by the unified dependency $m(T_s)$ values of T_s for the propellants. The corrected values of T_s are also included in Table 2. Obtaining differential characteristics for these propellants is based on the unified dependency $m(T_s)$.

Table 1 Propellant compositions

Propellants	A	B	C	D
Nitrocellulose, %	55	50	50	50
Nitroglicerine, %	20	20	20	20
Nitrosoamine, %	20	15	17	17
HMX (40 μm), %	——	10	10	——
HMX (10 μm), %	——	——	——	10
Ni, %	2	2	——	——
Processing additives	Up to 100%	Up to 100%	Up to 100%	Up to 100%

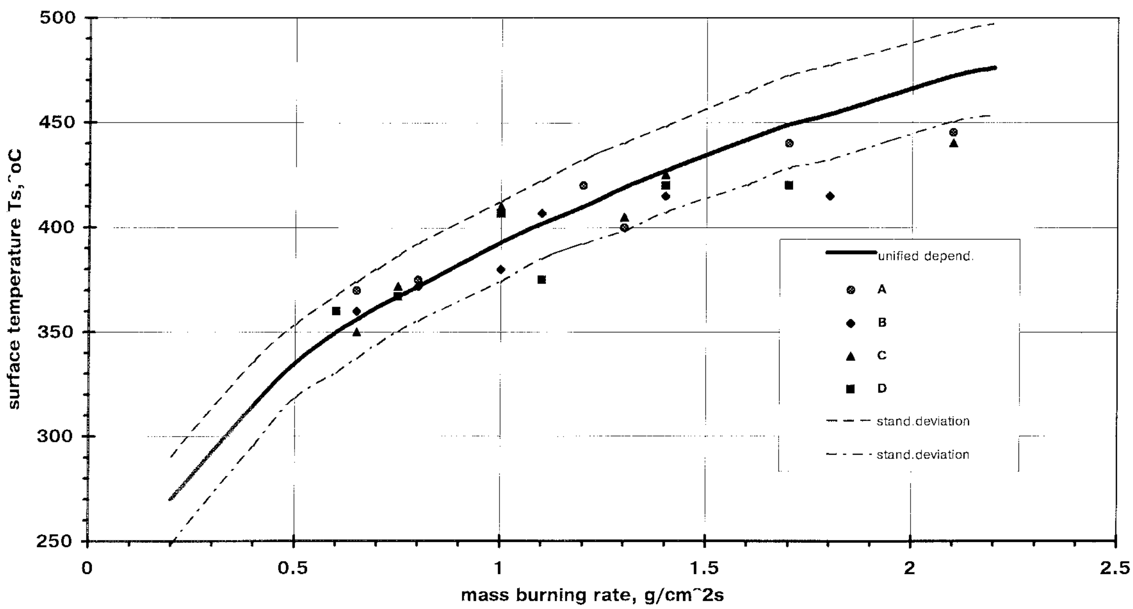

Fig. 1 Positions of T_s points of propellants A–D on the unified dependency $T_s(m)$.

Table 2 Values of mass burning rates m, g/cm^2 s, and burning surface temperatures T_s,°C, for propellants A–D

		$20p$, atm			$100p$, atm		
Propellants	Property	$-80T_0$,°C	$+20T_0$,°C	$+100T_0$,°C	$-80T_0$,°C	$+20T_0$,°C	$+100T_0$,°C
A	m	0.64	0.82	1.35	1.2	1.65	2.16
	T_s	370/350[a]	375	400/420[a]	420/410[a]	440	445/475[a]
B	m	0.64	0.82	1.12	1.12	1.36	1.8
	T_s	360/350[a]	375	380/400[a]	407/400[a]	415/425[a]	415/450[a]
C	m	0.64	0.77	1.3	1.02	1.34	2.14
	T_s	370/350[a]	370/365[a]	400/420[a]	410/390[a]	420	440/474[a]
D	m	0.61	0.74	1.06	1.02	1.38	1.74
	T_s	360/348[a]	365	375/395[a]	407/390[a]	420	420/450[a]

[a]Values following solidus are corrected by unified dependencies.

Table 3 Mass burning rates m, g/cm^2 s, and burning surface temperatures T_s,°C, for HMX

	$20p$, atm			$100p$, atm		
Property	$-170T_0$,°C	$+20T_0$,°C	$+100T_0$,°C	$-170T_0$,°C	$+20T_0$,°C	$+100T_0$,°C
m	0.57	0.7	0.86	1.75[a]	2.2	2.5[b]
T_s	438	450	470	508	520	520

[a]Pressure 75 atm. [b]Pressure 90 atm.

Table 3 contains data for m and T_s of HMX. These data were taken from Refs. 8 and 13. The density of the pressed HMX pellets was $\rho = 1.7$ g/cm^3.

The measurements of mass burning rate m and burning surface temperature T_s, which are shown in Tables 2 and 3, were used to obtain the following temperature and pressure sensitivities of the burning wave parameters: Temperature sensitivity of mass burning rate, $\boldsymbol{\beta} = (\partial \ln m/\partial T_0)_{p\text{-const}}$; temperature sensitivity of burning surface temperature, $\boldsymbol{r} = (\partial T_s/\partial T_0)_{p\text{-const}}$; and pressure sensitivity of mass burning rate, $\boldsymbol{\nu} = (\partial \ln m/\partial \ln p)_{T_0\text{-const}}$. All of the characteristics obtained for the investigated propellants were compared with the corresponding characteristics of pure HMX.

It is well known that temperature and pressure sensitivities play a significant role in theories of different combustion phenomena. These sensitivities are necessary for obtaining the criteria of stable propellant combustion (for small perturbations). The criteria have been suggested by Zel'dovich[14] and Novozhilov.[15,16] Zel'dovich's[14] criterion for stable combustion is as follows: $k < 1$, where $k = \boldsymbol{\beta} \cdot (T_s - T_0)$. Novozhilov's[15,16] criterion for stable combustion is as follows: $k^* < 1$, where $k^* = (k-1)^2/(k+1) \cdot r$. Criterion k^* is used when $k > 1$. Criterion k^* must be used when it is necessary to take into consideration that T_s is a variable. Note that the measured temperature sensitivities are necessary for different calculations in nonlinear theory of propellant combustion behavior and in particular for calculations of the response functions of different orders.[17]

Before calculating of the sensitivities and the criteria, however, it is necessary to evaluate the accuracy of the calculations. It is necessary to choose an adequate data processing technique.

Analysis of Accuracy of Differential Characteristics and Criteria

The procedure of differentiation of different experimentally obtained dependencies is connected with significant decreasing of the accuracy of characteristics that are obtained due to this procedure in comparison with the accuracy of the original dependencies. It can be shown that the usual practice of obtaining differential characteristics of burning wave parameters leads to large errors. Let us use the following formulas for estimating values β and r:

$$\boldsymbol{\beta} = \frac{|\ln m_2 - \ln m_1|}{T_{01} - T_{02}} \tag{1}$$

$$\boldsymbol{r} = \frac{T_{s2} - T_{s1}}{T_{01} - T_{02}} \tag{2}$$

where subscripts 1 and 2 are used to mark values at the beginning and at the end of the interval of differentiation.

Then we use the following regular formula[18] for calculation of standard absolute deviation δF of expression $F(x, y, z)$ as functions of absolute deviations δx, δy, and δz:

$$\delta F = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 \delta x^2 + \left(\frac{\partial F}{\partial y}\right)^2 \delta y^2 + \left(\frac{\partial F}{\partial z}\right)^2 \delta z^2} \tag{3}$$

The calculations of formulas for the relative standard deviations $\Delta\boldsymbol{\beta} = \delta\boldsymbol{\beta}/\boldsymbol{\beta}$ and $\Delta\boldsymbol{r} = \delta\boldsymbol{r}/\boldsymbol{r}$ yield the following equations:

$$\Delta\boldsymbol{\beta} = \frac{\sqrt{2}\Delta m}{|\ln m_2 - \ln m_1|} \tag{4}$$

$$\Delta\boldsymbol{r} = \frac{\sqrt{2}\Delta T_s(T_s - T_0)}{T_{s2} - T_{s1}} \tag{5}$$

It was assumed here that deviation δT_0 is very small. Values Δm and ΔT_s in Eqs. (4) and (5) are the standard relative deviations of m and T_s correspondingly obtained from the scattering of the experimental points of these parameters by the least-squares method.[18] The standard deviations are equal to $\Delta m = \pm 5\%$ and $\Delta T_s = \pm 5\%$ (for example, see Ref. 8). As a rule estimation $\Delta\beta$ by Eq. (4) gives $\Delta\boldsymbol{\beta} = \pm(15\text{–}30)\%$, and these deviations are acceptable. However, as a rule, estimation Δr by Eq. (5) gives $\Delta\boldsymbol{r} = \pm(100\text{–}400)\%$ or greater. It is obvious that these deviations are not tolerable, and Eq. (2) cannot be used for r estimations.

The solution of the problem is relatively simple: A smoothing procedure of experimental dependencies must be used before the differentiation. This procedure is widespread when differentiation of experimental dependency is processed.

The unified dependency $T_s(m)$ (its validity for the investigated propellants was established earlier) made the smoothing procedure easier. The unified dependency is represented by the following expression[8,9,12]:

$$m^2 = (\lambda\rho/Q^2) \cdot \left(\Re T_s^2/E\right) \cdot Q^* k_{01} \cdot \exp(-E/\Re T_s) \tag{6}$$

where $\lambda\rho$, $\Re$, E, and $Q^* k_{01}$ are constants, $E = 21$ kcal/mol, and T_s in Kelvin. Equation (6) allows the following connection between $\boldsymbol{r}$ and $\boldsymbol{\beta}$ to be established:

$$\boldsymbol{r} = \boldsymbol{\beta} \cdot \left[\frac{E}{2\Re T_s^2} - \frac{T_0}{T_s(T_s - T_0)}\right]^{-1} \tag{7}$$

Equation (7) allows us to show that practically $\Delta \boldsymbol{r} = \Delta \boldsymbol{\beta}$. Values r obtained by Eq. (7) are close to those obtained by Eq. (2); however deviation Δr is obviously much smaller.

Small deviations $\Delta \boldsymbol{r}$ and $\Delta \boldsymbol{\beta}$ allow us to obtain criteria k and k^* with not very high deviations [estimation r by Eq. (2) and then calculations of k^* will give extra-high deviations of Δk^*, much more than 100%]. Equation (3) and the expression $k = \boldsymbol{\beta} \cdot (T_s - T_0)$ give the following formula:

$$\Delta k = \sqrt{\Delta \beta^2 + \Delta T_s^2} \tag{8}$$

The corresponding standard relative deviation for Δk^* is as follows:

$$\Delta k^* = \frac{\Delta \beta \cdot \left[\sqrt{2k^2(k+1)^2 + 1}\right]}{k^2 - 1} \tag{9}$$

The contribution of ΔT_s in Eq. (9) is ignored because it is very small. Estimations of values Δk and Δk^* by Eqs. (8) and (9) show that under the investigated conditions the values of Δk comprise $\pm$(20–40)% and of Δk^* comprise $\pm$(20–100)%. These deviations are reasonable.

Thus, the suggested smoothing procedure using unified dependency $T_s(m)$ presented by Eq. (6) allows the sensitivities of burning rate and burning surface temperature to be received with good accuracy.

Results of Calculations, Analysis of Burned Surface Irregularities, and Discussion

Tables 4–7 show the obtained values $\boldsymbol{\beta}$ and $\delta\boldsymbol{\beta}$, $\boldsymbol{r}$ and $\delta\boldsymbol{r}$, k and δk, k^* and δk^*, correspondingly. All of the values in Tables 4–7 have been obtained on the basis of T_s corrected by the smoothing procedure using unified dependency (6) (see Table 2).

Table 4 shows that the $\boldsymbol{\beta}$ obtained values for the investigated propellants are low: $\boldsymbol{\beta} = 0{,}15$–$0{,}65$. This is a significant advantage for the studied propellants because simple double-base propellants have large $\boldsymbol{\beta}$ especially at elevated T_0: It can be about 1%/K or greater. The studied propellants have low $\boldsymbol{\beta}$ due to nitramine additions (because the pure HMX has a very low $\boldsymbol{\beta}$: 0,1–0,2%/K). Table 4 also shows that, as a rule, increasing pressure leads to decreasing $\boldsymbol{\beta}$ for all T_0, and increasing T_0 leads to increasing $\boldsymbol{\beta}$. Those are the common tendencies of dependencies $\boldsymbol{\beta}(p, T_0)$. Table 4 also shows that removal of the catalyst increases $\boldsymbol{\beta}$ (it shows that the addition of Ni powder decreases $\boldsymbol{\beta}$). Values $\boldsymbol{\beta}$ of propellant with a very small HMX particles and with catalyst at 100 atm are practically independent of T_0.

Table 4 Temperature sensitivities of mass burning rate $\beta = (\partial \ln m/\partial T_0)$, in %/K, and absolute standard deviations $\pm\,\delta\beta$, in %/K; values $\beta/\pm\,\delta\beta$ are given

	20p, atm			100p, atm		
Propellant	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C
HMX	0.108/0.037[a]	0.15/0.026	0.257/0.087	0.12/0.037[b]	0.13/0.026	0.16/0.088[c]
A	0.248/0.07	0.414/0.039	0.62/0.009	0.318/0.07	0.327/0.04	0.34/0.09
B	0.248/0.07	0.31/0.04	0.39/0.089	0.194/0.07	0.26/0.039	0.35/0.089
C	0.186/0.07	0.242/0.04	0.65/0.088	0.29/0.07	0.42/0.04	0.58/0.089
D	0.20/0.07	0.31/0.04	0.45/0.088	0.30/0.07	0.29/0.04	0.20/0.089

[a] $T_0 = -170$°C. [b] $T_0 = -170$°C, 75 atm. [c] Pressure 90 atm.

Table 5 Temperature sensitivities of burning surface temperatures $r = (\partial T_s/\partial T_0)$ and absolute standard deviations $\pm\,\delta r$; values $r/\pm\,\delta r$ are given

	20p, atm			100p, atm		
Propellant	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C
HMX	0.10/0.03[a]	0.16/0.027	0.30/0.103	0.06/0.02[b]	0.07/0.014	0.09/0.05[c]
A	0.204/0.058	0.39/0.037	0.72/0.102	0.315/0.07	0.37/0.04	0.45/0.12
B	0.206/0.06	0.29/0.037	0.425/0.096	0.186/0.068	0.278/0.04	0.43/0.1
C	0.51/0.19	0.22/0.036	0.75/0.1	0.34/0.08	0.38/0.035	0.765/0.11
D	0.165/0.058	0.334/0.04	0.485/0.095	0.278/0.066	0.31/0.04	0.356/0.11

[a] $T_0 = -170$°C. [b] $T_0 = -170$°C, 75 atm. [c] Pressure 90 atm.

Table 6 Values of Zel'dovich[14] criterion $k = \beta(T_s - T_0)$ and absolute standard deviations $\pm\,\delta k$; values $k/\pm\,\delta k$ are given

	20p, atm			100p, atm		
Propellant	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C
HMX	0.66/0.23[a]	0.65/0.12	0.95/0.33	0.81/0.25[b]	0.65/0.13	0.68/0.38[c]
A	1.07/0.31	1.47/0.16	1.98/0.3	1.56/0.36	1.37/0.18	1.28/0.34
B	1.07/0.31	1.10/0.15	1.17/0.27	0.93/0.34	1.04/0.16	1.23/0.32
C	0.80/0.3	0.83/0.14	2.08/0.3	1.36/0.34	1.68/0.18	2.18/0.34
D	0.86/0.3	1.07/0.15	1.33/0.27	1.41/0.34	1.16/0.16	1.01/0.32

[a] $T_0 = -170$°C. [b] $T_0 = -170$°C, 75 atm. [c] Pressure 90 atm.

Table 7 Values of Novozhilov[15,16] criterion $k^* = (k - 1)^2/(k+1)r$ (when $k > 1$) and absolute standard deviations $\pm\,\delta k^*$; values $k^*/\pm\,\delta k^*$ are given

	20p, atm			100p, atm		
Propellant	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C
A	0.01/0.01	0.23/0.05	0.45/0.07	0.38/0.08	0.16/0.04	0.08/0.03
B	0.18/0.2	0.02/0.02	0.03/0.015	——	0.003/0.001	0.06/0.02
C	——	——	0.5/0.07	0.16/0.04	0.46/0.08	0.6/0.08
D	——	0.07/0.07	0.1/0.03	0.26/0.065	0.04/0.02	0.001/0.05

Table 5 shows that obtained values $\boldsymbol{r}$ for the studied propellants comprise $\boldsymbol{r} = 0.186$–0.765 and for HMX $\boldsymbol{r} = 0.06$–0.3. Table 5 also shows that the common tendencies of the function $r(p, T_0)$ are the same dependencies that were predicted in Refs. 7 and 8: increase of $\boldsymbol{r}$ when T_0 increases and decrease of $\boldsymbol{r}$ when p increases. Propellant C (small HMX particles, catalyst) has the highest values of $\boldsymbol{r}$.

Using the data obtained in Tables 4 and 5 allows the criteria of stable combustion k and k^* to be estimated. Table 6 shows that HMX meets the condition $k < 1$ and that studied propellants as a rule does not meet this condition. Table 7 shows the estimated criteria k^* for regimes in which $k > 1$. It can be seen that all estimations give values k^* that meet the condition $k^* < 1$.

Two requirements must be taken into account here when comparing experimental data and theory. It is necessary that 1) the character of a combustion regime, stable or nonstable, be precisely determined and 2) the combustion process be one dimensional (because the theory of combustion stability and the processing of experimental data are based on the one-dimensional approach). Experience shows that the character of a combustion regime can be established by temperature profiles obtained by a microthermocouple method and by the time dependence of the burning rate. The profile reproducibility and small standard deviations of the burning rate and of different points of the profiles (first, burning surface temperature) are the indication of the stable combustion regime. The pulsations of the profiles (regular or nonregular) and of the burning rate time dependence are indications of the unstable regime. The chosen propellants, as well as HMX,[8,19,20] burn steadily under the investigated conditions. They have reproducible temperature profiles, smooth time dependence of burning rate, and small deviations Δm and ΔT_s (see earlier text).

Special work was performed to confirm the validity of the one-dimensional approach to the analysis of modern propellant combustion (also see Ref. 12). It was necessary because nitramines, as is well known, have a nonuniform burning surface.[11] Also nitramines create a liquid layer with bubbles and caverns on the burning surface of nitramine-containing propellants.

The quenched burning surface of the investigated propellants was obtained in different ways, by depressurization and by a spray of liquid, at pressures of 20 and 100 atm. The linear profiles of the surface microrelief was obtained by microscope analysis (accuracy ± 1 μm). The obtained linear profiles of the microrelief are very close to the profiles that were shown in Ref. 12 for simple double-base propellants. It is obvious that the burning process can be regarded as one dimensional if the large surface irregularities $x^{\tilde{}}$, in comparison with a characteristic length of burning wave, are rare. The thickness of the heat layer in solid l can be chosen as this characteristic length. It is natural to assume that the quantitative characterization of one dimensionality is the probability $\Psi_l(x^{\tilde{}})$ of encountering an irregularity of size $x^{\tilde{}}$ on length of l as a function of size $x^{\tilde{}}$. In fact, function $\Psi_l(x^{\tilde{}})$ is a fraction of l-long sections on a linear profile of the microrelief with a height difference $x^{\tilde{}}$ in the total number of sections (100–150 l-long sections were taken for every combustion regime). The combustion process can be regarded as one dimensional if the main part of this function, including the maximum of the function, is located at $x^{\tilde{}}$ that is significantly less than l. This one-dimensional case was obtained due to processing the experimentally obtained linear profiles of the surface microrelief of the chosen modern propellants. Typical examples of the obtained functions $\Psi_l(x^{\tilde{}})$ are shown in Figs. 2 and 3. Figure 2 shows function $\Psi_l(x^{\tilde{}})$ for propellant B at 20 atm. The thickness of the heat layer in solid l here is equal to 30 μm. It can be seen that the maximum of $\Psi_l(x^{\tilde{}})$ is located at x close to zero and that the main part of the function $\Psi_l(x^{\tilde{}})$ is located at $x < l$. Figure 3 shows function $\Psi_l(x^{\tilde{}})$ for propellant D at 100 atm. The thickness of the heat layer in solid l here is equal to 23 μm. It can be seen that the maximum of $\Psi_l(x^{\tilde{}})$ also is located at x close to zero and that the main part of the function $\Psi_l(x^{\tilde{}})$ also is located at $x < l$. These examples show that the probability of encountering on length l an irregularity $x^{\tilde{}}$ even at $x^{\tilde{}} \approx 0.5l$ is very close to 0.

Thus, the analysis of the burned surface irregularities of modern propellants confirms the one-dimensional character of the combustion under the investigated conditions. It implies that all of the methods of obtaining and processing experimental data used here are valid for modern propellants. Thus, the criterion k^* correctly predicts the combustion stability of the studied propellants and HMX under the investigated conditions.

Table 8 Pressure sensitivities of mass burning rates $\nu = (\partial \ln m/\partial \ln p)$

	$20p$–$100p$, atm		
Propellant	$-80T_0$, °C	$+20T_0$, °C	$+100T_0$, °C
HMX	0.85[a]	0.657	0.675
A	0.42	0.44	0.28
B	0.35	0.29	0.3
C	0.29	0.33	0.31
D	0.34	0.39	0.45

[a] $T_0 = -170$°C.

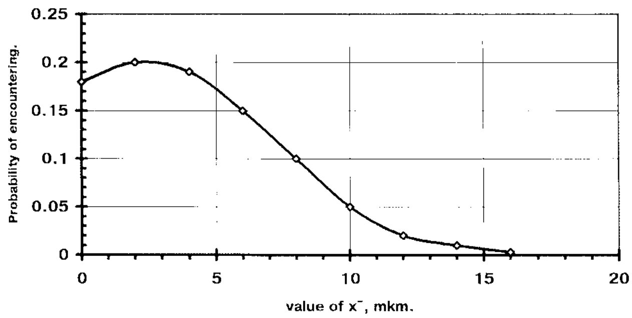

Fig. 2 Probability of encountering an irregularity of size $x^{\tilde{}}$ on length l, as dependence on $x^{\tilde{}}$: propellant B, 20 atm, T_0 = 20°C.

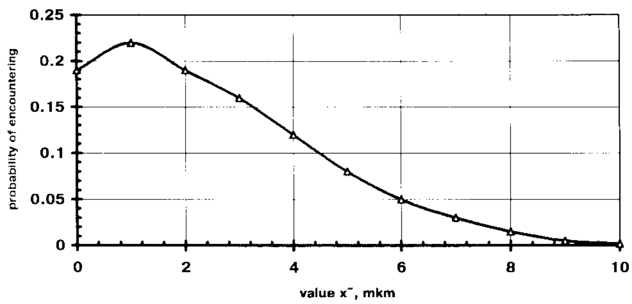

Fig. 3 Probability of encountering an irregularity of size $x^{\tilde{}}$ on length l, as dependence on $x^{\tilde{}}$: propellant D, 100 atm, T_0 = 20°C.

This work also contains differential characteristic ν, which is presented in Table 8. It can be seen that the propellants with HMX (propellants B and C) have very small values ν. These values ν are less than that for HMX and for ordinary double-base propellants with and without HMX. The removal of HMX (propellant A) or using small particles of HMX without Ni (propellant D) leads to increasing ν.

Conclusions and Future Work

Burning rates and burning surface temperatures have been obtained experimentally for four modern double-base propellants containing nitramine additions: 20% nitrosoamine and different amounts HMX with or without Ni catalyst. Temperature sensitivities of burning-wave parameters, burning rates and burning surface temperatures, have been estimated from the experimental data taken at pressures of 20 and 100 atm and at sample initial temperatures -80, $+20$, and $+100$°C. Evaluations of standard deviations of the estimations show that a smoothing procedure for dependencies of burning-wave parameters on pressure and initial sample temperature is needed to obtain correctly values of the sensitivities. The unified dependency connecting burning rates and burning surface temperatures was used for the smoothing procedures. It allows the sensitivities of burning rate and burning surface temperature to be obtained with good accuracy. The sensitivities are related to those of HMX. Calculations of criteria of stable combustion show that the Novozhilov criterion correctly predicts regimes of stable combustion of the investigated propellants and HMX. An analysis of burned surface irregularities of the propellants shows the one-dimensional character of the combustion. It confirms the validity of the experimental data processing used in this work and the appropriateness of the theory of solid combustion stability.

In future work the obtained results will be used for calculations of the response functions for the investigated propellants.

Acknowledgment

The work was supported by the Russian Foundation of Fundamental Investigations, Grant 97-03-32076a.

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