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Partial Burn Laws in Propellant Erosive Burning

S.V. Finjakov and A.A. Zenin

Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia.

ABSTRACT

Experimental and computer methods were developed for investigating the combustion phenomena in the propellants which burn in streams of hot gas flowing along the burn surfaces of the propellants. The experimental investigations allowed establishment of different dependencies for erosive burning. Computer solutions of the problem for double-base (DB) propellants showed a good agreement with the experimental results. The suggested variant of modified theory considers the change of heat release in solids, the real burn surface roughness, the nonisothermality of boundary layer and the effect of gas mass blow from the propellant burn surface into the gas stream. This modified theory was used for studying burn laws at 30-1000 atm and up to gas stream sound velocities for different DB propellants. It was found that gas stream leads to splitting of the propellant burn laws, $m = bp^{\nu}$. Pressure power (ν), in this case depends on gas stream velocity (W), diameter of the propellant tube canal (d) and gas stream temperature (T_W). It is because of this that these burn laws were named partial burn laws. They have the form $(m = bp^{\omega})\, w, d, T_w - const.$ The dependencies $\omega = f(w, d, T_w)$ were obtained by the modified theory. It was found that ω values mainly decrease when pressure increases beginning from ~200 to 400 atm and they can decrease up to ω = 0,1- 0,3. Similar results can be obtained for composite propellants.

NOMENCLATURE

p	Pressure
m_o	Propellant mass burn rate without gas stream
m	Propellant mass burn rate with gas stream, erosive burn rate
m^*	Propellant mass burn rate with isothermal gas stream
$\varepsilon = m / m_o$	Parameter of erosion, relative burn rate
z	Distance coordinate normal to burn surface
τ	Current time
d	Propellant canal diameter
h_s	Equivalent height of roughness at propellant burn surface
δ	Average real height of protuberances at propellant burn surface
Λ	Average distance between the protuberances
h	Average width of the protuberances
$W(z)$	Velocity of gas stream blowing along burn propellant surface
W_0	Velocity of isothermal gas stream

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W^*	Velocity of gas stream average across the canal
$T(z)$	Temperature profile of propellant burn wave
T_s, T_f	Temperatures of propellant burn surface and propellant flame
T_0, T_w	Propellant initial temperature and averaged gas stream temperature
q	Heat feedback by heat conductivity from gas to solid in propellant burn wave
Q	Heat release in solid in propellant burn wave
Q_g	Heat release in gas in propellant burn wave
Q_v	Propellant caloric power at constant pressure
$\Phi(z)$	Function of heat release rate in gas phase of propellant burn wave
Φ_0	Heat release rate in gas near to burn surface, $\Phi_0 \cong c_p\, m\, (dT/dz)_0$
L	Size of gas phase zone of propellant burn wave
D	Distance of z-integration
λ	Laminar heat conductivity of gas phase of burn wave
$\lambda_t(z)$	Turbulent heat conductivity of gas phase of burn wave
c, c_p	Specific heat of condensed and gas phase
ρ_1	Gas density
ρ_0	Density of isothermal gas flow
ξ_0	Coefficient of friction (Darcy coefficient) without gas stream (smooth surface)
ξ	Darcy coefficient with gas stream (rough surface)
η	Kinematic viscosity of gas
η_0	Kinematic viscosity of gas at the canal axis
V^*	Dynamic gas velocity, $v^* = W\sqrt{\xi/8}$, (cm/s)
l^*	Dynamic length, $l^* = \eta / v^*$
$\Phi(z)$	Nondimensional velocity of gas stream, $\varphi = W(z)/v^*$
φ_0	Nondimensional velocity of gas stream without gas blowing from the burn surface into gas stream
Z^*	Nondimensional z-coordinate, $z^* = z/l^*$
ϑ	Parameter of nonisothermality of boundary layer, $\vartheta = T_s / T_w$
θ	Nondimensional gas stream temperature, $\theta = T_w / T_f$
a^*	Gas stream sound velocity average across the canal
M	Average Max number of gas stream, $M = W^*/a^*$
ν	Pressure power of propellant burn laws without gas stream
ω	Pressure power of partial burn laws.

1. INTRODUCTION

The increase of propellant burn rate caused by the stream of hot gas blowing along the propellant burn surface is a well-known effect nominated as erosive burning. Experimental and computer methods have been developed for obtaining and predicting erosive burning rate of different propellants. As a rule, these works deal with propellant burn rates obtained experimently and computed burn rates under various gas dynamics conditions. The main drawback of the computing has been the simplification of the thermal structure of propellant burn waves (narrow burn zones in gas phase, wrong macrokinetic laws for reactions in gas and solid, constant burn surface temperature, absent or constant heat release in solid, and so forth). Real roughness of the burn surface which plays a very significant role in erosive burning also was not considered in earlier work[1-8]. Such approach distorted physical picture of erosive burning and did not allow real dependencies for erosive burn wave parameters to be established. New methods of erosive problem-solution have been suggested by using detailed information obtained experimentally[9-12] about geometrical and thermal structures and macrokinetics of normal burn waves (without gas stream) of different propellants. This complex approach consists of three steps. In the first step, all experimental information was obtained which could be received by modern methods for burn wave structures of different propellants burning under normal and erosive conditions. At this step, first of all the thermal burn wave structure was obtained by microthermocouple technique. The burn rates, temperature profiles, burn surface temperatures, heat release in solid, heat feedback from gas to solid, heat release rate in gas, and sizes of combustion zones were determined. Parameters of burn surface roughness for erosive burning were also obtained. In the second step, a new theory of erosive burning was created. This theory uses the information obtained at the first step for normal burning. Erosive burn wave parameters were calculated by this theory, and a comparison of experimental and calculated results was made. The agreement of the results showed that the theory is good enough for describing the erosive phenomena. It is evident that an experimental study of erosive burn wave structure can be made only at restricted values of pressure and burn rate (up to about 150 atm and 2-3 g/cm^{2}s). The procedure developed for calculations of erosive parameter can help to introduce a range of pressures and burn rates which are difficult in experimental study. The third step contains the computer study of erosive burning in a wide range of parameters of the process.

2. EXPERIMENTAL STUDIES

Experimental study of the thermal structure of double-base (DB) propellant burn waves was carried out by microthermocouple technique[10-15]. Normal burning was studied in a constant pressure bomb and erosive burning was studied in a model rocket motor up to 150 atm. Investigation of the real burn surface roughness of propellants which burned in erosive regime was made by microscope technique[10]. By generalising the existing and experimentally obtained information about surface roughness, the following unified law has been established[10-12]:

$$h_s/\delta = 2,26/(\Lambda/h) - 0,66/\sqrt{\Lambda/h} - 0,14/(\Lambda/h)^2 \quad (1)$$

It was also found that regime of gas flow at the erosive burning propellant surface must be described as regime of fully-manifested roughness. It implies that the friction coefficient (ξ_o) should be calculated by Prandtl's formula:

$$\xi_o = 0,25/[\log(h_s/3,7d)]^2 \quad (2)$$

Computer method of calculations consists of a numerical solution of the heat conductivity equation for burn wave propagating through the propellant. Calculations stop when stationary conditions are achieved. The following equation and boundary were used:

$$\partial/\partial z[\lambda_t(z)\partial T/\partial z] - c_p m \partial T/\partial z + \Phi(z)$$
$$= c_p \rho_1 \partial T/\partial\tau \quad (3)$$

$$z = 0;\ T = T_s;\quad \lambda\partial T/\partial z = c\,(T_s - T) - Q(m,p)$$
$$z = D;\ T = T_f;\quad \partial T/\partial Z = 0;\quad (D > L)$$

The following relations between T_s, m, Q and p were used[14-16]:

$$m = 1,8 \times 10^3 \exp(5000/T_s) \quad (4)$$

$$Q/Q_v = 0,17 - 0,103\exp(-0,0253/\sqrt{m}) \quad (5)$$

3. RESULTS

It is well-known that physical reason of erosive burning is increasing heat feedback from gas to solid due to turbulence appearing in gas boundary layer. Turbulent heat coefficient (λ_t) for isothermal boundary layer (without blowing from the burn surface) can be determined as

$$\lambda_t = \lambda/(d\varphi_o/dz) \quad (6)$$

The calculations of DB propellant erosive burn rates were carried out at 30-1000 atm for stream temperature $T_w = T_f$ and for Q_v = 600-1200 cal/g. A special procedure was developed for predicting distributions of heat release rates in gas phase of different propellants at high pressures. The results of these calculations have been described. The most impressive result is obtaining maximum of ε on the dependence, $\varepsilon(p)$. The maximum occurs at 200-500 atm. Before this, maximum values of ε increase monotonically and after that maximum values of ε decrease monotonically. The second result is the character of dependencies of ε (d) and ε (m_o): $\varepsilon \sim d^{-n}$, where n = 0,1-0, 2; exist $\sim m_o^{-1}$. The third result is the establishment of phenomenon of equalisation of erosive burn rates for various DB propellants. There exists practically unified dependence of m on parameters d, W, and p. The fourth result gives evidence for the absence of forces in combustion regime for DB propellant erosive combustion in a wide range of burn parameters (up to ~1000 atm). The forced combustion regime is a regime at which the burning is completely determined by heat feedback from gas to solid. It implies that the inequality $q >> Q$ must exist during the erosive burning. However, the calculation and experimental measurements in this study show that this inequality does not exist in conditions under consideration.

3.1 Modified Theory of Propellant Erosive Burning

The above results were obtained by the use of simplified theory of erosive propellant burning which was constructed within the framework of Zeldovich-Novozhilov's theory of propellant combustion. The main points of the calculations were as follows:

- Taking into consideration the main effect of the gas stream being blown along the burn surface, leading to rapid increase of gas heat conductivity because of turbulence.
- Neglecting the interaction of gas dynamics and chemical phenomena.
- Taking into consideration the real change of T_s and Q when ε changes.

The modified theory of propellant erosive burning considers the real existing effects: effect of gas mass blow from the burn surface into the stream and effect of boundary layer nonisothermality. This approach includes the law for friction with disappearing gas viscosity. It allows (i) to calculate the effect of two factors mentioned in the form of the gas velocity profile across the propellant tube canal with a good approximation and (ii) to solve by this way, the problem of considering the effects of gas mass blow from the surface and the layer nonisothermality. As to neglecting the interaction of gas dynamics and chemical phenomena, it is important to stress that under conditions of propellant burn waves this interaction does not play a significant role. This statement is based on peculiarities of functions of heat release rate in gas phase of propellant burn waves. These functions have the maxima close to burn surface[14-15] where the turbulent intensity is very small. It implies that the effect of the turbulent pulsation's on the function is also small.

Considering the effects of nonisothermality and gas mass blow from the surface, the modified theory of Kutateladze-Leontjev[17] is used. In this theory, the coefficient λ_t must be represented in the following form:

$$\lambda_t = \lambda / \{\beta\sqrt{8/\xi}.(d\varphi/dz^*).[k^2 + \Omega k + \Omega r] / [\sqrt{a}\,(2k+\Omega)]\} \tag{7}$$

where $\beta = (1+\vartheta)\,(\eta/\eta_o)$; $a = (1-\vartheta)b_o$; $\Omega = (1-\vartheta)\,G + \vartheta b_o$; $r = \vartheta G$;

$$k = \sqrt{a(a+\Omega+r)}\exp[\sqrt{a}(\varphi_o\sqrt{\xi_o/8}-1)] - \Omega/2$$

$$b_o = 8m/\rho_o W_o \xi$$

$$G = \alpha b_o / [\exp(\alpha b_o) - 1];\ \alpha = m^*/m$$

The two layer model of boundary layer model was used in this case. The model has the following formulae:

$$\varphi(z^*) = z^*;\ d\varphi/dz^* = 1;\ (0 \le z^* \le F)$$
$$\varphi(z^*) = F + 2{,}5\ln(z^*/F);\ d\varphi/dz^* = 2{,}5/z^*;\ (z^* \ge F) \tag{8}$$

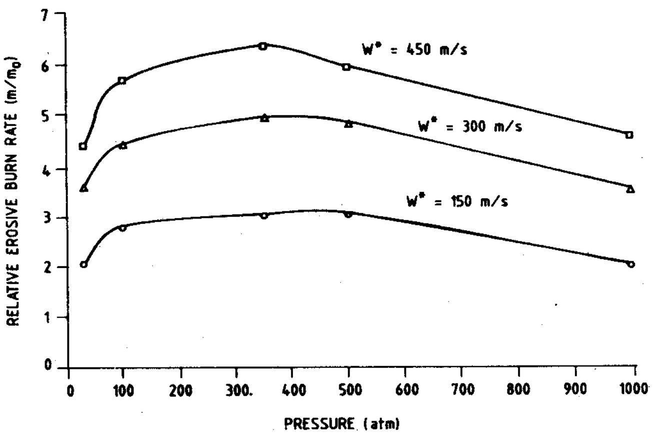

Figure 1. Dependencies of relative erosive burn rate on pressure. Propellant A. $(T_w/T_f) = 1$.

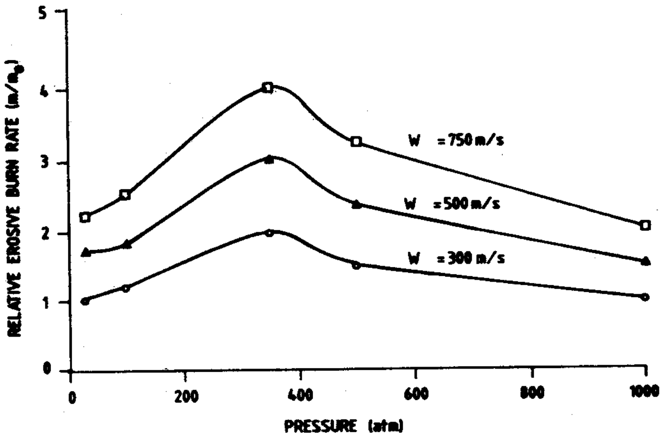

Figure 2. Dependencies of relative erosive burn rate on pressure. Propellant B. $(T_w/T_f) = 1$.

Under the present experimental conditions, function F $\cong$ 8,48. Equations (7) and (8) describe in a slightly simplified form, the gas dynamics of boundary layer of propellant erosive burning in the modified theory. The computing of the erosive burning characteristics (burn rate, temperature and heat release rate profiles in distance) begins by introducing into computer file, the initial temperature profile and function of heat release rate in gas which were obtained experimentally at normal conditions. At high pressures (p >150 atm), the profiles and functions were obtained for normal conditions by preceeding procedure established by Zenin and Finyakov[10]. Experiments and evaluations show that at p > 100-150 atm, thermal structure of combustion waves of DB propellants becomes very simple and functions $T(z)$ and Φ (z), can be represented[10-12] by the following equations:

$$\Phi(z) = \Phi_o \exp(-\Phi_o z / Q_g m) \quad (9)$$

$$T(z) = T_f - (T_f - T_s) \exp(-\Phi_o z / Q_g m) \quad (10)$$

The solution of the erosive problem is obtained by computing heat conductivity equation on two-dimensional grid by the numerical method at the distance coordinate running along the parameter D and back. Parameter λ_t was taken from Eqn (7). Integration has been performed with respect to τ up to obtaining steady propagating burn wave and establishing stabilisation of all parameters. Erosive burn rate and temperature profile of erosion burn wave have been obtained for each regime as a result of such integration.

4. RESULTS & DISCUSSIONS

The first result of calculations is confirming to the validity of the dependencies $\varepsilon = \varepsilon(p, d, m_o, W)$ which were obtained by the simplified theory. There are some refinements in ε values. However, the principal character of the dependencies as a whole does not change. The main attention in the calculations by the modified theory was focused on obtaining burn laws for a wide range of pressures (30-1000 atm) and gas velocities (up to sound). Double-base propellant of caloric power from 600 to 1200 cal/g has been studied. A special study was undertaken by varying stream temperature (T_w) from flame temperatures (T_f) up to the temperature which leads to propellant extinction.

Figures 1 and 2 demonstrate dependencies $\varepsilon = \varepsilon(p)$ obtained by the modified theory at different values of W for propellant A (Q_v = 600 cal/g) and propellant B (Q_v = 1200 cal/g). The maximum ε_m can be seen on these figures at 350-500 atm. It can also be seen that decrease in Q_v increases the values of ε_m. Values of ε_m depending on W can be very high (for example, $\varepsilon_m = 6{,}5$ for propellant A at $W = 450$ m/s and p = 350 atm). Effects of decreasing θ for propellant

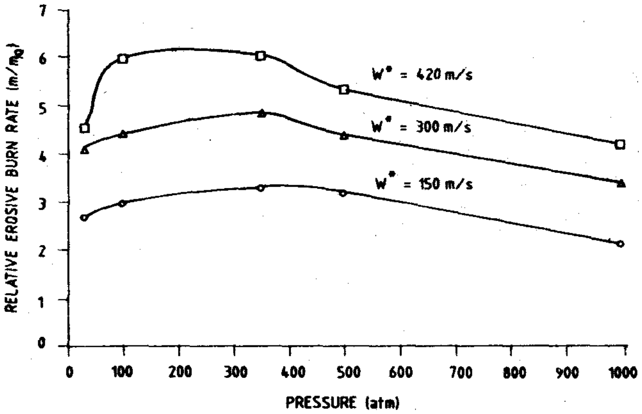

Figure 3. Dependencies of relative erosive burn rate on pressure. Propellant A. $(T_w/T_f) = 0.82$.

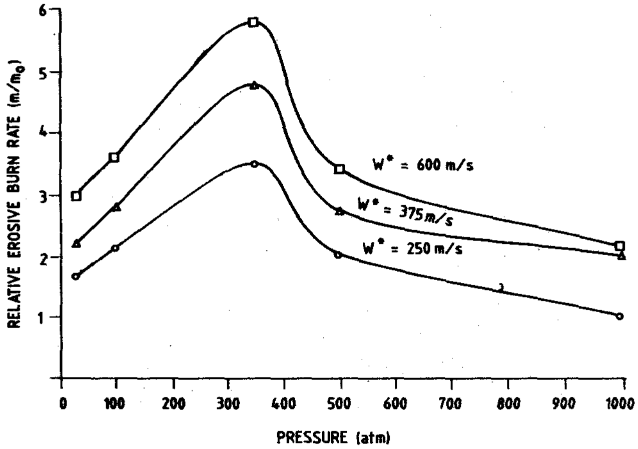

Figure 4. Dependencies of relative erosive burn rate on pressure. Propellant B. $(T_w/T_f) = 0.54$.

A and propellant B is given in Figs 3 and 4, respectively. It can be seen that a decrease in θ leads to slight increase in ε_m for propellant A and large increase in ε_m for propellant *B*. For example, when θ decreases from 1 to 0,54 for propellant B, the value ε_m at W = 600-750 m/s increases from 4 to 5,8. This phenomenon can be explained by the fact that erosion depends on mass velocity of the stream $\rho_1 W$ and because of that the decrease in θ, $\rho_1 W$ increases and hence ε increases. As can be seen, the phenomenon is very essential for propellants of low Q_v, which tend to undergo erosion. The results obtained imply that the temperature factor of the stream under these conditions is not important. However, when θ decreases to low values, close to propellant extinction, decrease in ε takes place.

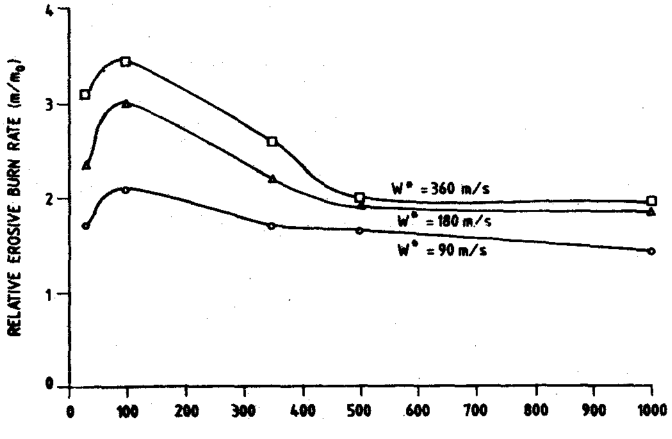

Figure 5. Dependencies of relative erosive burn rate on pressure. Propellant A. $(T_w/T_f) = 0.52$.

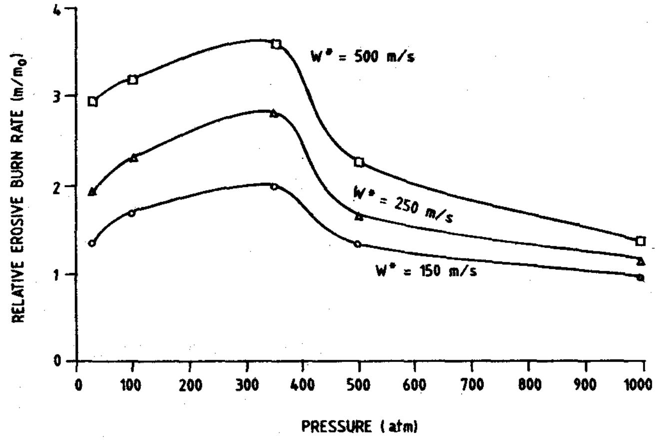

Figure 6. Dependencies of relative erosive burn rate on pressure. Propellant B. $(T_w/T_f) = 0.38$.

Figures 5 and 6 show a very significant bellowing ε_m for propellants A and B. It can be seen that $\varepsilon_m = 3{,}5$ at $\theta = 0{,}52$ for propellant A and $\varepsilon_m = 3{,}6$ at $\theta = 0{,}38$ for propellant B. Temperature factor plays the main role here. It is interesting to note that change in position of ε_m for propellant A takes place when the propellant is close to extinction. ε_m for the propellant B takes place at 100 atm. All the results obtained by numerical calculations using modified theory were for d = 1,1 cm. Similar results can also be obtained for other values of d.

The data obtained allow the estimation of change in burning laws due to parameters W, d, and

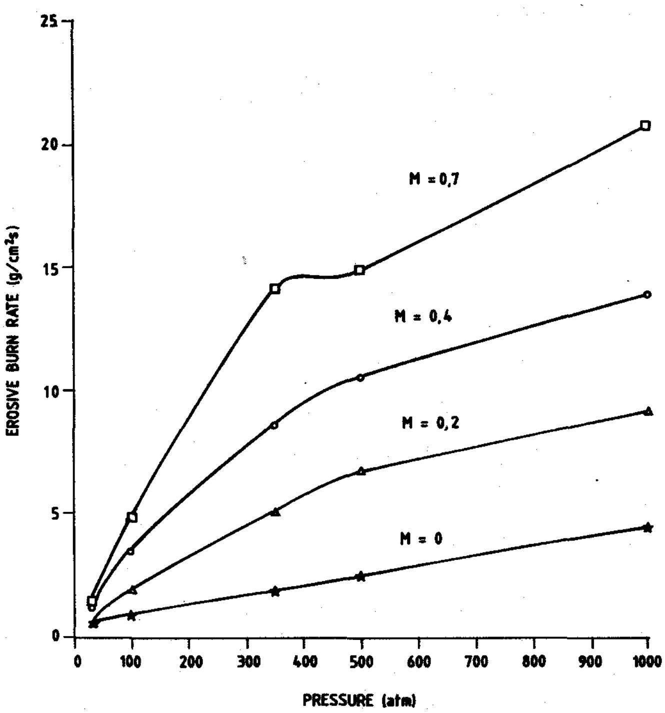

Figure 7. Partial burn laws of propellant A. $(T_w/T_f) = 1$

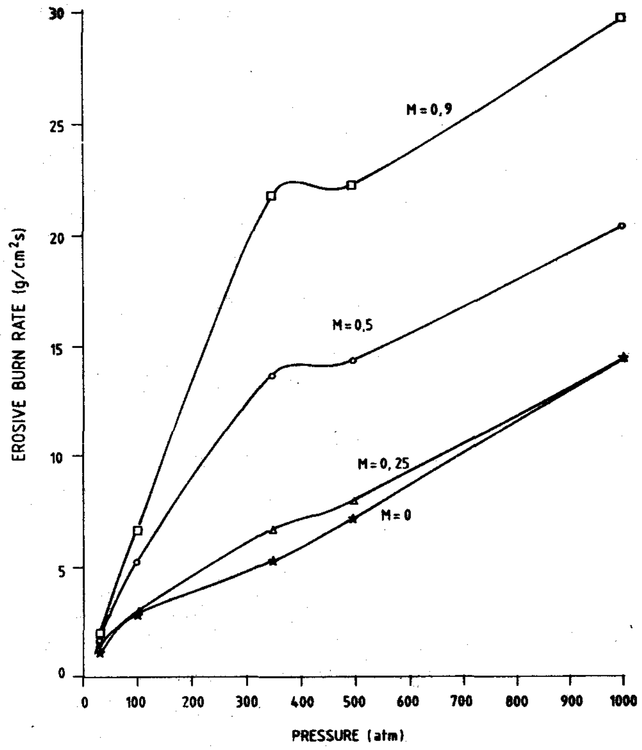

Figure 8. Partial burn laws of propellant B. $(T_w/T_f) = 1$

θ. It is obvious that gas stream leads to the splitting burn law of propellant in a multitude of burn laws. These burn laws can be named partial burn laws. The simplest form of burn law is $m_o = b_o\, p^{\nu}$. The simplest form of partial burn laws is

$$(m = bp^{\omega})w,d,\theta - const \qquad (11)$$

Evaluations of dependence, $\omega = \omega(W, d, \theta)$ can be made as a first approximation by the formula

$$\omega = \nu + (p/\varepsilon)dp/d\varepsilon \qquad (12)$$

Analysis of Figs 1-6 and Eqn (12) shows that at $p < p(\varepsilon_m)$, there must exist inequality $\omega > \nu$, since at these pressures $dp/d\varepsilon > 0$. And at $p > p(\varepsilon_m)$, these must exist inequality $\omega < \nu$ since at these pressures $dp/d\varepsilon < 0$.

However, the real picture is more complex because the real dependencies $m(p)$ must be represented in different range of pressures by different laws. Figures 7 and 8 show the real dependencies $m(p)$ for propellant A and propellant B at $\theta = 1$ for different Max number, *M* of gas stream. It can be seen that indeed there are at least three regions of different character of *m*(*p*): below 350 atm, at 350-500 atm and at 500-1000 atm. Calculations show that curves *m*(*p*) hold its shape during bellowing θ. The ω calculated through obtained values on the basis of *m*(*p*) for different *M*, *p* and θ, for propellants A and B, are given in Tables 1 and 2. It is worthwhile to note that the studied propellants have the following characteristics under normal conditions (without gas stream):

Propellant A:

$m = 0{,}048.p^{0{,}635}$ (g/cm²s) at $1 \leq p \leq 700$ atm

$m_o = 0{,}0045.p$ (g/cm²s) at $p \geq 700$ atm

$(T_f = 1620$ K)

Propellant B:

$m_o = 0{,}227.p^{0{,}54}$ (g/cm²s) at $1 \leq p \leq 450$ atm

$m_o = 0{,}0144.p$ (g/cm²s) at $p \geq 450$ atm

$(T_f = 2773$ K)

Table 1. Values of burn law parameters for propellant A

$\theta = 1$

	M = 0,7 cm/s; W^* = 440 m/s			M = 0,4 cm/s; W^* = 250 m/s			M = 0,2 cm/s; W^*=125 m/s	
p (atm)	30-350	350-600	600-1000	30-350	350-700	700-1000	30-500	500-1000
b [g/cm^{2}s. (atm)$^{-\omega}$]	0,093	5,74	0,65	0,14	0,49	1,038	0,057	0,22
ω	0,863	0,154	0,502	0,706	0,49	0,38	0,762	0,546
ν	0,635	0,635	1	0,635	0,635	1	0,635	1

$\theta = 0,82$

	M = 0,7 cm/s; W^* = 410 m/s			M = 0,4 cm/s; W^* = 235 m/s			M = 0,2 cm/s; W^* = 115 m/s	
p (atm)	30-350	350-600	600-1000	30-350	350-600	600-1000	30-500	500-1000
b [g/cm^{2}s. (atm)$^{-\omega}$]	0,214	1,99	0,73	0,098	2,256	0,476	0,083	0,277
ω	0,67	0,29	0,448	0,756	0,216	0,464	0,683	0,488

$\theta = 0,52$

	M = 0,7 cm/s; W^* = 410 m/s		M = 0,4 cm/s; W^* = 235 m/s				M = 0,2 cm/s; W^* = 115 m/s		
p (atm)	30-500	500-1000	30-100	100-350	350-600	600-1000	30-100	100-500	500-1000
b [g/cm^{2}s. (atm)$^{-\omega}$]	0,22	0,146	0,026	0,15	0,38	0,028	0,016	0,105	0,068
ω	0,468	0,54	0,896	0,512	0,354	0,763	0,924	0,514	0,585

Table 2. Values of burn law parameters for propellant B

$\theta = 1$

	M = 0,9 cm/s; W^* = 750 m/s			M = 0,5 cm/s; W^* = 400 m/s			M = 0,25 cm/s; W^* = 200 m/s		
p (atm)	30-350	350-500	500-1000	30-350	350-500	500-1000	30-350	350-500	500-1000
b [g/cm^{2}s. (atm)$^{-\omega}$]	0,114	13,52	2,9	0,166	6,53	0,22	0,163	0,536	0,05
ω	0,895	0,0813	0,329	0,756	0,127	0,656	0,639	0,432	0,808
ν	0,54	0,54	1	0,54	0,54	1	0,54	0,54	1

$\theta = 0,54$

	M = 0,9 cm/s; W^* = 650 m/s		M = 0,5 cm/s; W^* = 400 m/s		M = 0,25 cm/s; W^* = 210 m/s		
p (atm)	30-500	500-1000	30-500	500-1000	30-350	350-600	600-1000
b [g/cm^{2}s. (atm)$^{-\omega}$]	0,24	0,73	0,227	5,49	0,5	0,0214	0,019
ω	0,696	0,515	0,631	0,128	0,34	0,89	0,91

$\theta = 0,38$

	M = 0,9 cm/s; W^* = 550 m/s		M = 0,5 cm/s; W^* = 300 m/s		M = 0,25 cm/s; W^* = 150 m/s		
p (atm)	30-500	500-1000	30-500	500-1000	30-350	500-750	750-1000
b [g/cm^{2}s. (atm)$^{-\omega}$]	0,286	0,822	0,306	1,67	0,152	0,054	0,547
ω	0,544	0,366	0,498	0,248	0,552	0,73	0,382

Tables 1 and 2 show that a significant decrease in ω takes place close to $p(\varepsilon_m)$. Values of ω can be very small here. For example, propellant B has ω = 0,0813 at M = 0,9, θ = 1, 350-500 atm, and ω = 0,127 at M = 0,5, θ = 1, 350-500 atm (Table 2). Propellant A has ω = 0,154 at M = 0,7, θ = 1, 350-600 atm (Table 1). In general, in the middle region of the pressures for both the propellants, $\omega \cong 0{,}2\text{-}0{,}5$.

A very important result was obtained for high pressure. Tables 1 and 2 show that very small values of ω can be obtained here also. For example, propellant B has $\omega = 0{,}128$ at $M = 0{,}5$, $\theta = 0{,}54$ (500-1000 atm), and propellant A has $\omega = 0{,}38$ at $M = 0{,}4$, $\theta = 1$, (500-1000 atm). In general, at high pressure, propellant A has as a rule $\omega \cong 0{,}45\text{-}0{,}6$ and propellant B has a wide range of $\omega(0{,}3\text{-}0{,}9)$; however at $\theta = 0{,}38$, $\omega \cong 0{,}25\text{-}0{,}38$. Similar results can be obtained for composite propellants.

5. CONCLUSION

The results obtained show that the use of gas stream could be a very efficient method of decreasing pressure power in burning laws of many DB propellants. This method can be especially useful at high pressures where the pressure power for all the propellants is equal to one under normal conditions (without gas stream).

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