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Mathematical Modelling of Nonstationary Physico-Chemical Processes in Large-Sized SPRM Pyrotechnical Ignition System

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ABSTRACT

In this paper, the laws of the unstable wave processes accompanying the combustion abnormal mode in the large-sized solid propellant rocket motor (SPRM) pyrotechnical ignition system (IS) are investigated by numerical method. The IS contains the main (cylindrical) channel (MC) having uniform perforation over the lateral surface. The left MC boundary is blocked and the right boundary is uniformly perforated. The whole perforation is hermetically sealed from outside. The additional (cylindrical) channel (AC) (an initial impulse amplifier) with uniform perforation over the lateral surface is installed into the MC cavity, coaxially to MC. The right AC boundary is blocked, and the time-varying high-temperature gas flow, containing incandescent particles is supplied from initiator, equipped with a fast burning compound, through AC left perforated boundary. To imitate the exploitation conditions, the IS is placed in cylindrical imitation chamber (imitative SPRM).

In a number of cases, before the beginning of the IS operation, a situation can be realised when the pelletised solid propellant (PSP) mass is non-uniformly distributed along the IS AC length, and the greater part of the AC lateral perforation is blocked by the PSP inserted in the IS MC. Under these conditions, the effect of abnormal strengthening of the pressure waves at the AC boundaries is possible. For describing the abnormal nonstationary physico-chemical processes, a mathematical model is developed. For the check-up of this complex model, the numerical calculation results have been compared with the results of the fire stand tests for the regular IS and the engine. The numerical analysis of the unstable wave process development in the AC has shown that the rise of the pressure with an ever increasing amplitude is realised at the moment, when a shock wave reflects alternately, on the left and on the right AC boundaries. The effect of the pressure waves' abnormal strengthening can result in the destruction of the AC and other elements of the IS structure and exert undesirable influence on the development of the ignition process of the SPRM charge. On the basis of the numerical analysis results, a modified design of the pyrotechnical IS construction having increase operational reliability is suggested.

NOMENCLATURE

t	Time of the process
x	Longitudinal coordinate
z	Radial distance from the granulated elements surface to its centre
L	Length of the IS (AC and MC)
F	Area
F_P	Pores area
d_{AC}, d_{MC}	Initial diameters of the pelletised elements, placed in AC and MC cavities
F_{AC}	Cross-section area of the IS AC

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F^p_{AC}, F^p_{MC}	Total perforation areas in the AC and MC
θ_0	Coefficient of the perforation openings contraction
F_b	External surface of the identify length boundary
$F_{\Sigma perf}$	Total perforation openings area per unit boundary length
$\dot{P}_1$	Damping pressure on the surface with area $(F_b - F_{\Sigma perf})$
P_U	Total perimeter of the PSP pores in the direction of the velocity of CP motion U
m	PSP porosity
ω_{AC}, ω_{MC}	Masses of PSP, placed in the AC and MC cavities
ω_{AC1}, ω_{MC1}	Masses of the one pelletised element of the PSP, placed in the IS AC and MC
T	Temperature
T_{ig}	Critical temperature
T_h	Temperature of the beginning of the 'heterogeneous' exothermic reaction
$K_h(T_c)$, K_{0h}, E_h, Q_h	Rate coefficient, pre-exponent, activation energy and the thermal effect of the 'heterogeneous' reaction
$\bar{S}_c$	PSP surface relative area joined up to combustion
P	Pressure
P_o	Environmental pressure
ρ_{mix}	Density of the combustion products (CP) mixture
P_{mix}	Pressure of the CP mixture
U	Flow velocity of the CP mixture
E_{sp}	Specific energy of the CP mixture
ρ	Density
ρ_g	Gas phase density
γ_c	Relative mass concentration of the c-phase in the CP mixture
ρ_c, μ_c	Granulated elements (GE) material density and the linear rate of the GE combustion
R, k	Gas constant and the adiabatic exponent
R_o	Universal gas constant
a, b	Mass concentrations of the CP, coming into the AC through its left boundary and formed at PSP burning
C_p C_V, C_c	Specific heat capacities of the CP mixture gas phase and the condensed phase
τ_t^{ω}	Tangential stress of the CP friction in filtering through the PSP pores
M	Rate of the mass interphase exchange (the sum of gas incomes and flow rates of the CP)
G_U^{imp}, G^E	Losses and income of the amounts of motion and energy owing to the CP flow between spaces. G^E also takes into account the work done when CP flow-out through the perforation
Q_E	Rate of the interphase energy exchange
$\dot{G}_c$	Mass CP flow rate from AC into MC
λ	Thermal conductivity coefficient
η_1	Dimensionless coefficient of the hydrodynamic resistance
$N\mu$	Nusselt thermal criterion
q_{cp}, q_h	Thermal flows from the CP and from 'heterogeneous' chemical reaction
$\sqrt{K}$	Characteristic size
K_p	PSP penetration factor
Re	Reynolds criterion
C_{fo}	Friction resistance coefficient
S	Entropy
ΔH_{298}	Specific enthalpy of kg of PSP

Subscripts & Superscripts

o	Corresponds to initial conditions, the parameters of the gas, originally filling PSP pores
$j = 1$	Corresponds to the CP mixture
$j = 2$	Corresponds to the CP coming from the initiator, through the AC left boundary
$j = 3$	Corresponds to PSP CP
c, g	Corresponds to the parameters of the condensed (solid) phase and the gas phase, respectively

s	Corresponds to the parameters at the GE surface
	Corresponds to the parameters of the gas phase and the c-phase mixture
h	Corresponds to the parameters of the 'heterogeneous' chemical reaction
st	Corresponds to the stationary values of parameters
U	Corresponds to the parameters in the direction of the CP motion velocity *U*
x	Corresponds to the parameters in the direction of longitudinal coordinate
b	Corresponds to the parameters on the boundary
	Corresponds to the parameters of the perforations.

1. INTRODUCTION

The intraballistic parameters in the initial stage of the large-sized SPRM operation in many respects are determined by the physico-chemical processes occurring in the pyrotechnical IS and subsequent heat effect of the IS charge combustion products (CP) on the motor main charge. For such IS the considerable dependence of technical characteristics and the operational safety from passing quality of aggregate of physico-chemical processes or heating-up and PSP combustion, propagation of the gaseous reaction products on IS volumes, passing of the aggregate of heterogeneous reactions with emission or absorption of energy and heat-mass exchange processes. That is why, it is important to know how to calculate accurately parameters in the IS, especially taking into account the possibilities of appearance of the combustion abnormal modes. In this paper, the laws of the unstable wave processes accompanying the combustion abnormal mode in the large-sized SPRM pyrotechnical IS is investigated using numerical methods.

2. DESCRIPTION OF IGNITION SYSTEM

The solution of the problem is carried out for one of the most widespread schemes[1] of the SPRM IS. The sectional diagram of the IS is shown in Fig. 1. The IS contains the main (cylindrical)

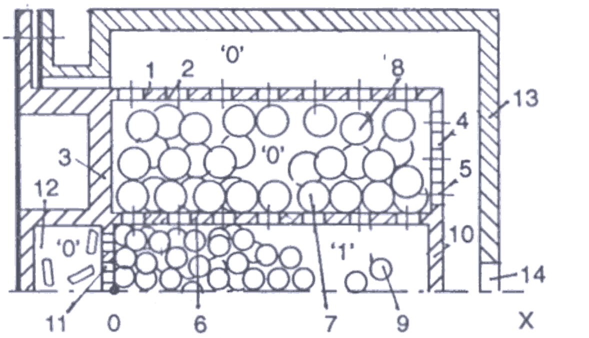


Figure 1. Sectional diagram of the pyrotechnical ignition system, installed in the imitation chamber (large-sized SPRM, having the propellant charge made from an inert material).

channel (MC) (1) having uniform perforation (2) over the lateral surface. The left MC boundary (3) is blocked and in the right boundary (4), there is uniform perforation (5). The whole perforation is hermetically sealed from outside. The additional (cylindrical) channel (AC) (6) (an initial impulse amplifier) with uniform perforation (7) over the lateral surface is installed into the MC cavity (1), coaxial to MC. Granulated elements (GE) (8), (9) having the spherical form and pressed from the pyrotechnic mixture (PTM) are packed densely in the cavities of the channels (1), (6). The right AC boundary (10) is also blocked, and the time-varying high-temperature gas flow, containing incandescent particles is supplied from initiator (12) equipped with a fast burning compound through left perforated boundary (11). Ratio of channel length to the diameter is more than one and preset to be equal to 1.2 for MC, and 10 for AC. In the number of cases, before the beginning of the IS operation, a situation can be realised when the PSP mass (9) is non-uniformly distributed along the length of the IS AC (6), and the greater part of the AC lateral perforation (7) is blocked by the PSP (8) inserted in the IS MC (1). The IS is installed in the imitation chamber (IC) (13), which is intended for imitating service conditions, for example, of the large-sized SPRM free volume and geometrical sizes. At the right end of IC (13), there is a hole (14) intended for exhausting the differential pressure up to the normal level.

Usually, the process in the IS, and then in the IC is developed in the following way. From the initiator (12) CP arrive at AC (6), where they heat-up and ignite the PSP (9). From the AC (6) the CP arrive in the MC (1), where they heat-up and ignite the PSP (8). When the pressure in the MC (1) attains the level exceeding the destruction pressure of the hermetic sealing, the hermetic sealing is destroyed and the CP begin to arrive in the front volume of the IC (Fig. 1).

3. MATHEMATICAL MODEL

When constructing the mathematical model of physico-chemical processes proceeding in the SPRM IS and IC, the following set of assumptions are made:

(a) The cold gas which originally occupied the pore space of the channels, the hot CP coming through the AC left boundary into the estimated ranges, and the CP of the PSP, all form the chemically nonreacting mixture, the flow of which is nonstationary and follows the laws of flow of ideal gas;

(b) In the CP mixture condensed particles can be present, the rate and the temperature of which coincide with the corresponding parameters of the gas;

(c) Losses by friction and heat transmission from the CP mixture into PSP and channel walls are taken into account by introducing into the relevant parts of equations, the amount of motion and energy of the source-type members;

(d) All of the condensed particles generated by PSP combustion deposit right away on the GE surface, because of this assumption, a convective term in the continuity equation for the condensed phase is dropped;

(e) GE are fixed in space, and only their geometrical sizes change gradually on burning. No particular flow over each GE is considered;

(f) The initial porosity of PSP is considered to be prescribed.

With these assumptions, one-dimensional differential equations of the CP mixture nonstationary motion between the GE, along the IS AC are written in the following form (for the multicomponents biphase mixture of the ideal gases):

$$\frac{\partial}{\partial t}\left(F_p \cdot \rho_{\text{mix}j}\right)+\frac{\partial}{\partial x}\left(F_p \cdot \rho_{\text{mix}j} \cdot U\right)=\frac{\partial M_j}{\partial x},$$
$$t>0,\quad 0\le x\le L,\quad j=\overline{1,3} \tag{1}$$

$$\frac{\partial}{\partial t}\left(F_p \cdot \rho_{\text{mix}} \cdot U\right)+\frac{\partial}{\partial x}\left(F_p \cdot \rho_{\text{mix}} \cdot U^2\right)+F_p \cdot \frac{\partial P_{\text{mix}}}{\partial x}$$
$$=\frac{\partial G_U^{imp}}{\partial x}-P_U \cdot \tau_t^U \cdot \bar{S}_U \tag{2}$$

$$\frac{\partial}{\partial t}\left(F_p \cdot \rho_{\text{mix}} \cdot E_{sp}\right)+\frac{\partial}{\partial x}\left(F_p \cdot \rho_{\text{mix}} \cdot U \cdot E_{sp}\right)$$
$$+\frac{\partial}{\partial x}\left(F_p \cdot P_{\text{mix}} \cdot U\right)=\frac{\partial Q_E}{\partial x}+\frac{\partial G_E}{\partial x} \tag{3}$$

$$\frac{\partial}{\partial t}\left(F_p \cdot \rho_{\text{mix}} \cdot \gamma_c\right)=P_U \cdot \rho_c \cdot u_c \cdot \gamma_{c_3}-\frac{\partial}{\partial x}\left(G_c \cdot \gamma_c\right) \tag{4}$$

$$E_{sp}=C_{ef} \cdot T_{\text{mix}}+\frac{U^2}{2} \tag{5}$$

$$C_p=C_{p_0} \cdot (1-a-b)+C_{p_2} \cdot a+C_{p_3} \cdot b \tag{6}$$

$$a=\rho_{\text{mix}2}/\rho_{\text{mix}} \tag{7}$$

$$b=\rho_{\text{mix}3}/\rho_{\text{mix}} \tag{8}$$

$$C_V=C_{V_0} \cdot (1-a-b)+C_{V_2} \cdot a+C_{V_3} \cdot b \tag{9}$$

$$C_{ef}=C_V \cdot (1-\gamma_c)+C_c \cdot \gamma_c \tag{10}$$

$$R \quad C_p - C_V \tag{11}$$

$$k=\frac{C_p}{C_V} \tag{12}$$

$$\rho_g=\rho_{\text{mix}} \cdot (1-\gamma_c) \tag{13}$$

$$F_p = F_{AC} \cdot m, \text{ (axial direction)} \quad (14)$$

$$P_{mix} = \rho_{mix} \cdot (1 - \gamma_c) \cdot (k-1) \cdot \left(E_{sp} - 0.5 \cdot U^2\right)$$

$$\bar{S}_U = \left(1 - \bar{S}_c^U\right) + \bar{S}_c^U \cdot \psi(\delta_U) \quad (16)$$

$$\bar{S}_c^U = 0, \text{ when } u_c = 0 \quad (17)$$

$$0 < \bar{S}_c^U \leq 1, \text{ when } u_c > 0 \quad (18)$$

$$\psi(\delta_U) = \left[1 - \frac{\partial_U}{\partial_{cr}}\right]^2 \quad (19)$$

$$\delta_U = \frac{2}{C_{fo}^U} \cdot \frac{\rho_c}{\rho_{mix}}$$

$$\delta_{cr} = 4.0 \quad (21)$$

$$= \quad (22)$$

$$\tau_t^U = \eta_{1U} \cdot \rho_{mix} \cdot U^2/8 \quad (23)$$

$$\frac{\partial T_c}{\partial t} = \frac{\lambda_c}{C_c} \cdot \frac{1}{z^2} \left(\quad \right), \quad (24)$$

$$T_s \geq T_{ig} \quad (25)$$

$$\frac{\partial T_c}{\partial t} = u \quad \frac{\lambda_c}{C_c \cdot \rho_c} \cdot \frac{1}{z^2} \cdot \frac{\partial}{\partial z}\left(z^2 \cdot \frac{\partial T_c}{\partial z}\right)$$

$$0 \leq z \leq d_{AC}/2, \; t > 0 \quad (26)$$

Boundary conditions

when $z = d_{AC}/2$, $\partial T_c/\partial z = 0$; (27)

when $z = 0$ and $t > 0$,

$$\frac{\partial T_s}{\partial z} = q_{cp} + q_h = \alpha_{cp} \cdot \frac{(T_{mix} - T_s)}{\lambda_c} + \frac{Q_h \cdot K_h(T_c)}{\lambda_c} \quad (28)$$

$$\begin{cases} K_{0h} \cdot \exp\left\{ \quad E_h \right. \\ 0, \end{cases} \quad (29)$$

For the GE burning surface ($u_c > 0$), as additional boundary condition, the equation for temperature on the surface (burning condition) is allowable.

$$T_s = \theta\,(P_{mix}, T_0) \quad (30)$$

Basic relations suggested by the Russian scientist V.P. Bobryshev (1973) are used to account for the possible erosive effect in GE burning. The basis of this procedure is the solution of the asymptotic equations of heat conduction and diffusion in the gas phase of the burning propellant. The distinctive feature of Bobryshev's model is based on the fact, that for every particular solid propellant there is no need to know a threshold (critical) value of the velocity of the flowing-over gas flux, below which there is no erosive burning. According to this procedure, the erosive coefficient ε, is determined on the basis of the following relationships:

$$\varepsilon = \sqrt{0.5 + \sqrt{0.25 + [\kappa_o \cdot \eta_T \cdot th(-\eta_T/30)]^2}} \quad (31)$$

$$\eta_T = (0.675 \cdot \eta_s + 2.1) \cdot th(\eta_s/3.25) \quad (32)$$

$$\eta_s = 2.2 \cdot \rho_{\text{mix}} \cdot |U| \cdot \sqrt{C_{fo}/2} \quad \overline{\rho_c \cdot u_c^{st}} \quad (33)$$

$$\kappa_o = 0.39 \quad (34)$$

$$\sqrt{C_{fo}/2} = [5.5 + 2.5 \cdot \ln(\text{Re} \cdot \sqrt{C_{fo}/2})]^{-1} \quad (35)$$

The last equation is solved by the iteration method. For the first approximation it is assumed that $C_{fo} = 0.04$.

For the description of the hydrodynamic and the heat exchange processes in the porous medium, the authors use the procedure[4,5], based on the model of the integral characteristics of systems.

The heat exchange coefficient α_{CP} consists of three components: they are owing to convective phenomenon realised in filtering CP through PSP pores, α_f; owing to CP radiation, α_{rad}; owing to the deposition of incandescent particles on the PSP surface, α_{cont}. Values of α_{rad} and α_{cont} are determined from the correlations[1]. To find the value of α_f the following correlation[5] is used:

$$\alpha_f = Nu_T \cdot \lambda_{\text{mix}} \cdot \bar{S}_c/\sqrt{K_P} \quad (36)$$

Insofar as the intensity of changes of gas dynamics parameters on AC volume is considerably greater than the speed with which the thermal parameters vary, the utilisation of the last of criteria relations (including a heat exchange coefficient), obtained in stationary conditions is allowable. This statement is coordinated with data obtained by B.P. Zhukov, V.V. Vengerskiy, Yu.N. Kovalyov and A.M. Lipanov as well as Bobryshev *et al*[6]. According to these data, application of the stationary conditions criteria relations for calculation of the processes in the initial stage of the IS operation is correct, if:

$$\lambda_{\text{mix}} / P_{\text{mix}} \cdot C_p \quad \frac{1}{6\alpha_f^2}\left[\frac{\partial}{\partial t}(\ln T_{\text{mix}}) + r_f \cdot \frac{\partial}{\partial t}(\ln |U|)\right] \le 0.03 \quad (37)$$

A coefficient $r_f = 0.2$ is to be used in case of laminar mode of the CP mixture flow, and for turbulent mode $r_f = 0.5$.

The physico-chemical processes proceeding in the initiator (12), IS MC (1) and IC (13) (Fig. 1) are simulated in the thermodynamic statement[1,6]. All flow-rate characteristics are determined in accordance with the relations given[6,7].

4. BOUNDARY CONDITIONS FOR GASDYNAMIC PROBLEM

Combination of gasdynamic parameters in boundaries of adjacent ranges with different dimensions (Fig. 1, '0' - '1' - '0' - '0') is carried out by means of the algorithm of 'decay of a random breakage[6,8]. In the same way the boundary conditions are formulated on the other AC and MC boundaries. For determination of the flow parameters on internal surfaces of the calculated range boundaries ('1') (Fig. 1, '6"), the conditions of dynamic compatibility[1] are used. We shall consider the singularity of application of these conditions for perforated boundary, which is partially covered by GE. The influence of the separation phenomenon, which is observed as the CP flow through the IS perforation, do not take into account, as far as the IS has small wall thickness.

$$F_b \cdot m \cdot \left[\rho_{mix} \cdot U\right]_1 = F_{\Sigma perf} \cdot \theta_o \cdot \left[\rho_{mix1} \cdot U\right]_2 \quad (38)$$

$$F_b \cdot m \cdot \left[\rho_{mix} \cdot U^2\right]_1 + F_b \cdot m \cdot P_{mix1}$$
$$= F_{\Sigma perf} \cdot \theta_o \; \rho_{mix} \cdot U^2\Big]_2 + F_{\Sigma perf} \cdot \theta_o \cdot P_{mix2}$$
$$+ \left(F_b - F_{\Sigma perf} \cdot \theta_o\right) \cdot P^*_{mix1} - (1-m) \cdot F_b \cdot P_{mix1} \quad (39)$$

$$\frac{U_2^2}{2} + \left(\frac{k_b}{k_b - 1}\right) \cdot \frac{P_{mix2}}{\rho_{mix2}} = \frac{U_1^2}{2} + \left(\frac{k_b}{k_b -}\right) \frac{P_{mix1}}{\rho_{mix1}} \quad (40)$$

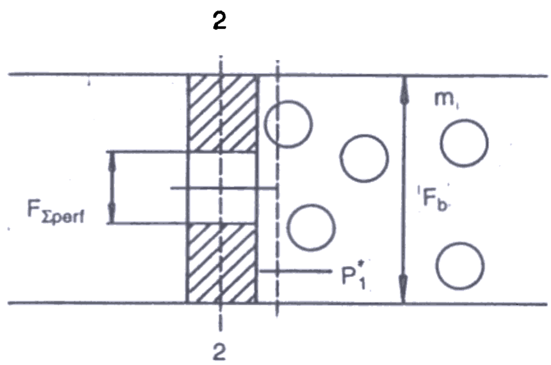
In the equation for impulses we shall assume that $P^*_{mix} \approx P_{mix1}$. The system of Eqns (38)-(40) has two solutions. And, only one of these solutions, which corresponds to the supersonic mode of CP flow ($U_1 > C_1$, where C is sound velocity), will correspond to a condition of entropy increase (ΔS):

$$\Delta S = \frac{R_b}{k_b -} \ln \left[\frac{P_{mix1}}{P_{mix2}} \; \frac{\rho_{mix2}}{\rho_{mix1}}\right]^{k_b} \quad (41)$$

Starting from this solution, at $t = 0$, from the system of Eqns (38)-(40) it is possible to obtain the following relations:

$$2\left(1 - \psi \frac{k_b - 1}{2k_b}\right)\Bigg[\qquad - 2\left(1 - \psi \frac{k_b - 1}{2k_b} \quad \psi \frac{k_b + 1}{k_b}\right. \quad (42)$$

$$\rho_{mix1} = \psi \cdot$$



$$P_{mix1} = P_{mix2} + \rho_{mix2} \cdot U_2 \cdot (U_2 - U_1)$$

where

$$\frac{\theta_o \cdot F_{\Sigma perf}}{m \cdot F_b} \quad (44)$$

The process of CP flow through flowing boundaries of the regions in a greater part of a period of PSP ignition is critical. When the critical conditions of the outflow will be broken, the perturbations introduced by the CP, which flowing through the boundary, will not themselves essentially influence the character of the process. Therefore, later on, the flowing boundary's nonflowing conditions can be given.

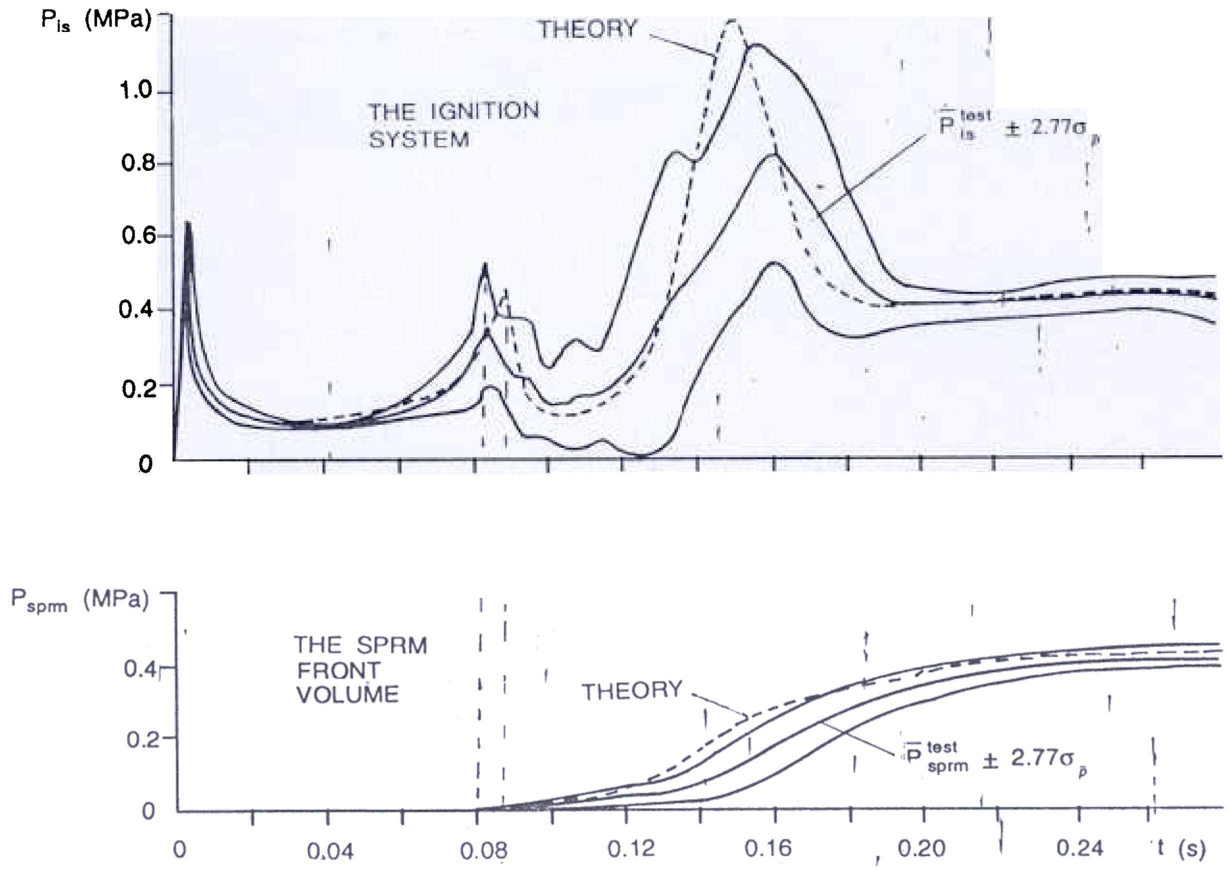


Figure 3. Comparison of the numerical calculations results (dashed lines) with the fire stand tests results (continuous lines) for the pyrotechnical ignition system for the large-sized SPRM, having the propellant charge made from an inert material.

The approximation of different equations is carried out on the non-uniform grid. A small step of the GE surface is chosen, and then it is increased according to the geometric progression law.

The rest of the equations of the system (the initiator, IS MC and the large-sized SPRM), having the propellant charge made from an inert material (the imitation chamber), are not complex to solve.

6. COMPARISON WITH TEST DATA

For the check-up of the developed complex mathematical model of physico-chemical processes, the numerical calculation results have been compared with those from the fire stand tests. The tests have been executed for the regular PT IS (Fig. 1), mounted in the large sized SPRM. Figure 3 shows dependence of pressure on time in the IS body P_{IS}^{test} (a pressure gauge was installed in the IS flange plug), and in the front volume of the SPRM combustion chamber (IC front volume) P_{SPRM}^{test} (two pressure gauges were installed in the engine body beside the front-end face surface of the propellant charge). Each of the curves represents the average result of five fire stand tests. Lowermost and uppermost curves characterise the bilateral symmetrical confidence interval of the pressure spread $\bar{P}_{IS}^{test}$ and $\bar{P}_{SPRM}^{test}$, and with confidence probability of 0.95. Curves, corresponding to the theoretically calculated pressures are shown by dashed lines. It is quite clear, that the calculated and the experimental curves (Fig. 3) are in good agreement both on amplitude, and on frequency.

7. SIMULATION RESULTS & DISCUSSION

Investigations were carried out for PTM with the following chemical compositions: technical

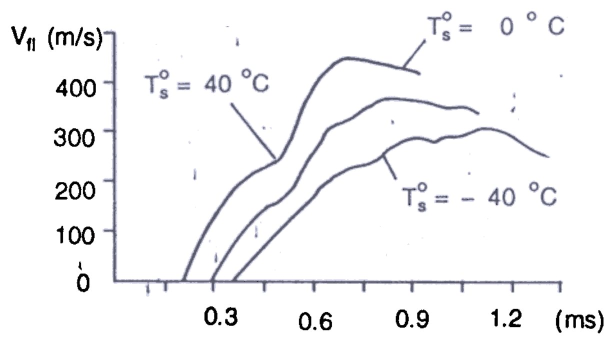


Figure 4. Flame front propagation velocity along the ignition system additional channel volume as a function of the process time and the granulated elements initial temperature.

barium nitrate - 60 per cent, titanium powder - 35 per cent, binding solution containing *Mg* compounds and graphite - 5 per cent. The basic initial data: ρ_c = 2900 kg/m^3; T_{ig} = 1090 K; T_{mix} = 3500 K; k = 1.276; γ_c = 0.62; L = 0.24 m; d_{AC} = 0.0095 m; d_{MC} = 0.0120 m; F_{AC} = 0.5 × 10^{-3} m^2; F_{MC} = 28.5 × 10^{-3} m^2; F^p_{AC} = 0.0065 m^2; F^p_{MC} = 0.040 m^2; ω_{AC} = 0.09 kg; ω_{MC} = 5.0 kg; ω_{AC1} = 0.0010 kg; ω_{MC1} = 0.0017 kg; u_c^{st} = 0.02 m/s at P_{mix} = 1 MPa; ΔH_{298} = − 2414 kJ/kg; λ_{mix} = 8.494 × 10^{-5} kJ/(m.sec.K); C_{ef} = 1387 J/(kg.K).

The analysis of results of numerical investigations of laws of the evolution of the physico-chemical processes in the pyrotechnical IS reveals the following.

PSP inflammation in the IS AC occurs under substantially nonstationary conditions. After PSP complete inflammation the gradual degeneration of combustion nonstationarity is observed. Variation of the PSP initial temperature (T_s^o = - 40 °C, 0 °C, + 40 °C) has shown, that the flame front propagation process over the PSP surface (Fig. 4) has shown temperature sensitivity. From Fig. 4 it is visible, that in temperatures range from - 40 °C up to + 40 °C the PSP complete ignition time changes from 0.93 ms up to 1.30 ms.

Calculations were fulfilled in the case, when, before the beginning ot the IS operation, the greater part of the AC (6) lateral perforation (7) is blocked (Fig. 1) by the PSP (8) inserted in the IS MC, and the PSP mass (9) is nonuniformly distributed along the IS AC length.

In Fig. 5, the spatial profiles of the CP pressure and flow velocity values in consecutive moments of the time are presented. At the moment of the time t = 0.26 ms occurs CP flow in the IS AC from the initiator with the sound velocity. After the beginning of the flame front propagation on the AC length, occurs a shock wave, which is propagated along the AC (t = 0.75 ms). At the moment of a

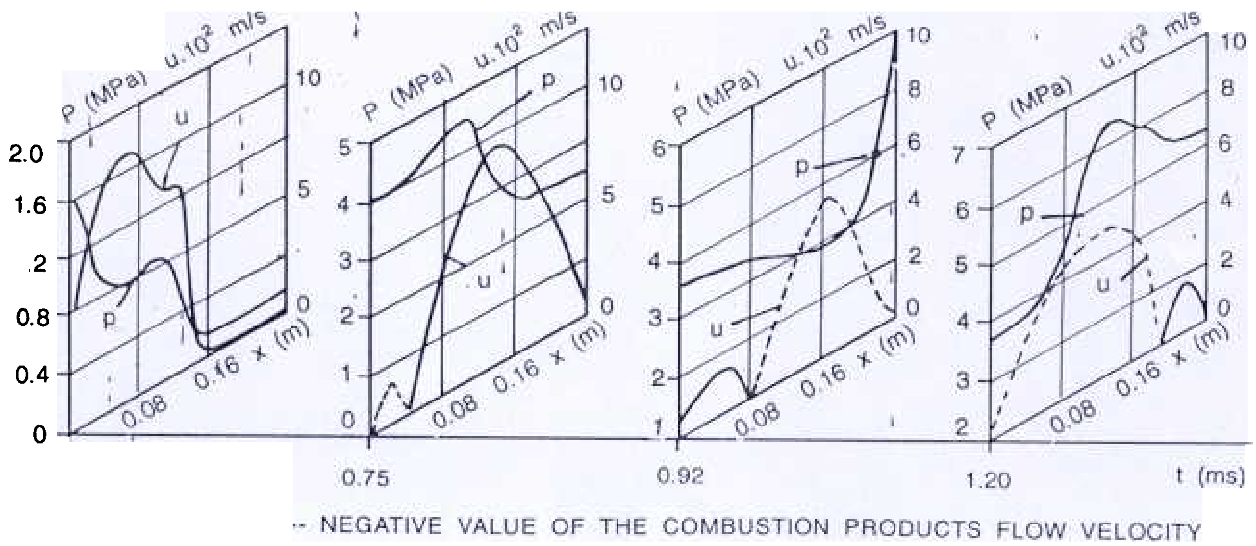


Figure 5. Evolution of the process dynamics in the ignition system additional channel

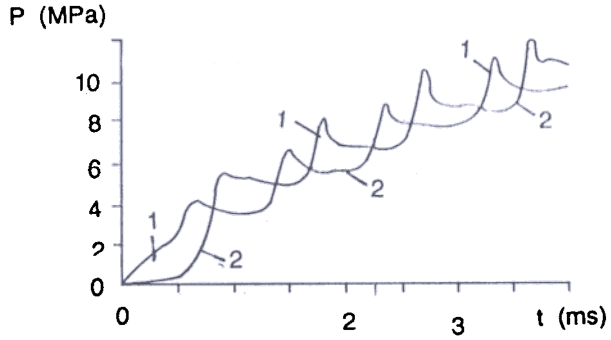


Figure 6. Dependence of the combustion products pressure adjacent to left (1) and right (2) ignition system additional channel boundaries on the time of the process.

shock wave reflection from the right AC end face, the pressure peak is created there (t = 0.92 ms). After this the shock wave propagation begins towards the AC left-hand boundary direction (t = 1.20 ms). On consecutive reflection of the longitudinal shock wave from the AC boundaries, the wave intensity increases. Figure 6 shows dependence of pressures adjacent to the left (1) and right (2) boundaries of IS AC on the time of the process. The rise of the pressure with an ever increasing amplitude is realised at the moment, when a shock wave reflects alternately, on the left (1) and on the right (2) AC boundaries. The reflected waves, arising at left-hand AC boundary, are propagated on the CP, which are largely braked by the previous reflected wave, and the waves reflected from the AC right boundary, are propagated on CP, which already have counter velocity. Therefore, the wave velocity in the straight direction (Fig. 6) exceeds the reflected wave velocity. The numerical analysis of the unstable wave process development in the AC has shown that the amplitude of the serial pressure rises at the AC boundaries can exceed the average pressure level by 3-6 times. The effect of the abnormal strengthening of the pressure waves can result in the destruction of the IS AC body and other elements of the IS structure, and exert unfavourable influence to the development of the ignition process of the SPRM charge. In particular, the SPRM propellant charge may not ignite at all. Also, the appearance of the intermittent burning (chuffing) mode is possible. The chuffing is very much probable in the small-sized SPRM as well as in the large-sized SPRM with a high intrachamber loading coefficient.

The influence of the initial nonuniform distribution of a granulated charge was investigated for the first time in the ordnance science, even in the last century. These investigations, marked in fact the beginning of the systematic study of the nonstationary periodic processes, accompanying the solid propellant burning, among which are the phenomena of chuffing and low-frequency instability, observable in the modern SPRM, and were executed by Maj. Gen. of the Russian Army, Nickolay V.Kalakoutsky, the outstanding Russian scientist in the fields of metallurgy, physical metallurgy and ordnance. The programme of Kalakoutsky's investigations included several thousand experiments (1876-1878), directed towards the search for the most rational method of realisation of the powder test of the steel gun barrels. Kalakoutsky[11] described the course of investigations and the results obtained from his voluminous work. Its translation in France demonstrated that his work on determination of pressure of the powder gases in gun barrels received ample recognition. In 1880 it was published in the Journal 'Revue d'artillerie' and at the same period it was issued as a separate brochure[12,13]. It is important to note, that Kalakoutsky had touched upon a question on the propagation of oscillatory motion of the gases long before experiments carried out by J. Viyel, the French chemist engaged in ignition powders. Kalakoutsky's investigations exerted a significant influence on the advancement of the gun production for a long time[14]. Consequently, this effect was investigated analytically by Betekhtin *et al*[15].

Now, the important precussor for the correct description of the physico-chemical phenomena, accompanying the intermittent burning of the solid propellant, is a series of experimental work of Marshakov[16,17]. These works are devoted to the substantiation of the hypothesis about cell-pulsating mechanism of the burning of the solid propellant. It is known, that the solid propellant burning surface represents an oscillatory system with an infinite number of degrees of freedom and the above mentioned mechanism permits to take into account the influence of the microscale phenomena on the intermittent burning process.

8. PREVENTION OF PYROTECHNICAL IGNITION SYSTEM ABNORMAL MODE OF OPERATION

Calculations demonstrate, that it is possible to prevent the occurrence of the above described IS abnormal mode of operation. On the basis of the numerical analysis results, the PT IS construction design is suggested to be modified and a sectional view is shown in Fig. 7. This IS scheme has an increased operational reliability which is realised by the suppression of the described abnormal effect. To provide for this, the IS AC (the central perforated tube 8) is executed multisectionally (Fig. 7), and each of the sections is supplied with PSP (17). Prior to the commencement and during the PSP ignition period all the sections mentioned are interconnected gasdynamically. After PSP ignition in each of the sections, the cavities of these sections are automatically isolated from one another and the PSP burning lasts in each of the isolated sections. Thus, the possibility of the shock waves propagation along the IS AC cavity and, accordingly, the occurrence of the effect of the pressure wave self-strengthening up to values considerably exceeding normal level, is excluded.

9. CONCLUSION

Numerical analysis conducted on the abnormal mode development in the SPRM IS has shown that the amplitude of the serial pressure rises at the IS AC boundaries and can exceed the average pressure level by 3-6 times. The effect of the pressure waves abnormal strengthening can result in the destruction of the IS AC and other elements of the IS structure and exert undesirable influence on the development of the ignition process of the SPRM charge. On the basis of the numerical analysis results, a new pyrotechnical IS construction design is suggested. This IS design has an increased operational reliability.

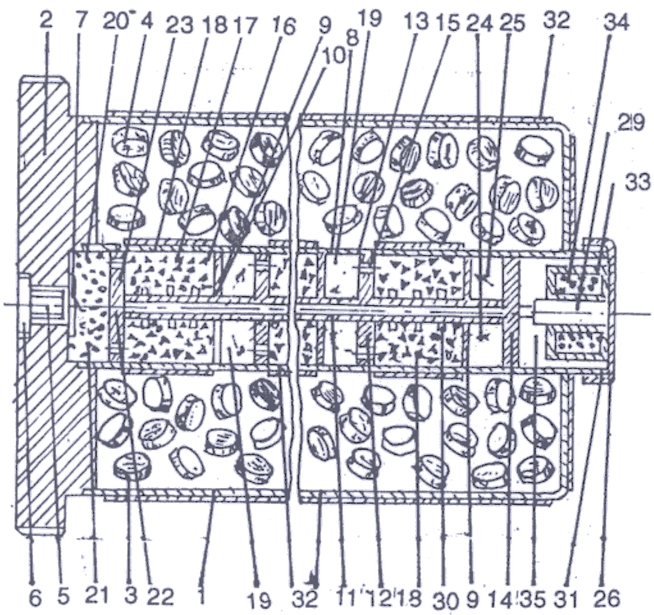


Figure 7. Sectional view of the modified design of the large-sized SPRM pyrotechnical ignition system, which has an increased operational reliability.

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