Ignition of solid rocket propellants – selection of authored works and literature review

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Please cite as: CHEMIK 2016, **70**, 1, 27–32

Introduction

Classic primers used for ignition of solid rocket propellants are based on black powder which produces significant amount of gas products per the following reaction [1]:

$74KNO_3 + 30S + 16C_6H_2O \rightarrow 56CO_2 + 14CO + 3CH_4 + 2K_2S + 4H_2 + 35N_2 + 19K_2CO_3 + 7K_2SO_4 + 2K_2S + 8K_2S_2O_3 + 2KCNS + (NH_4)_2CO_3 + C + S + 665$ kcal/kg

Main disadvantage of the black powder is the fact it is difficult to obtain repeatable ballistic characteristics that depend strongly on type of used charcoal and temperature of wood charring [2]. Uniqueness of black powder structure and short working time with simultaneous high pressure increase at the moment of ignition excludes application of black powder in state-of-the-art systems containing solid rocket propellants. Three types of primers are used for ignition of solid rocket propellants: pyrotechnic, pyrogenic and hypergolic [3].

Solid rocket propellant ignition theory is based on three fundamental postulates: reaction in gas phase, in solid phase and heterogeneous phase. Gas phase theory stipulates that ignition process is controlled by reaction between propellant and oxidiser, which is to evaporate probably including atmospheric oxygen. In the gas phase theory it is accepted that propellant undergoes exothermic reaction in solid phase with omitting heat emission and diffusion to gap phase. According to the heterogeneous phase theory, solid oxidiser decomposes to form of a gas oxidiser that reacts exothermically with propellant surface. Ignition model for hypergolic bipropellants is a special case of heterogeneous theory and assumes there is no external heating. Three review papers can be found in literature aiming to briefly discuss each of the aforementioned theories: Price [4], Kulkarni [5] and Hermance [6]. The purpose of primers in engines using solid rocket propellants is to increase thermal state of propellant to the degree that enables the ignition and its sustaining for a specific period of time. It was observed that in order to obtain optimum ignition it is important to ensure proper interaction of temperature and pressure as a function of time. General requirements for primers can be defined as follows [7, 8]:

- Propellant surface temperature should be raised above autoignition point.
- Pressure in engine chamber shall increase above minimum pressure required for stable propellant combustion.
- Ignition delay, i.e. time from applying electric pulse till obtaining 10% of pressure peak in combustion chamber should be maintained in strictly defined range.
- Time between ignition and 10-90% engine pressure should be sufficiently short, otherwise - due to heat exchange – more heat will be abstracted that it is generated by primer gases.
- The rate of change of pressure over time (dp/dt) in engine chamber should not be too high in order not to cause undesirable pressure peaks and shock loads. On the other hand it cannot be to low, as this could result in instability and delayed ignition.
- The primer should meet required limitation for size, weight and method of connection with chamber containing propellant.
- The primer should also meet environmental protection and storage requirements with determined initiation method and electric properties.

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Calculations and numerical simulations

The aim of the conducted calculations was to develop basis for designing apparatus allowing measurement of energy emitted by pyrogenic tablets. An essence of the conducted tests was measurement of total energy and its emission distribution over time. To that end, sensors for measuring heat exchange were used. The sensors were resistance thermometers made of thin metal foil (thickness ~0.1 μm) coating an insulator. Such sensors have response time of 1 μs order and sensitivity sufficient for the planned measurements. An important issue is determination of shape and main dimensions of measurement chamber, as well as conditions inside the chamber to be optimum for the measurement. Before starting to construct test apparatus, number of numerical simulations was conducted in order to determine estimated chamber dimensions, distance between sensors and test jacks and determination of volume of propagated gases. It was assumed that igniting tablet is cylinder-shaped of 4 mm diameter and 3 mm height with tablet material density equal to 1.6 g/cm^3, combustion rate – 4 cm/s, combustion product temperature – 2483K and that only one flat side of tablet is burning. Total combustion time for tablet is 75 ms, therefore for measurement of energy emission distribution over time was reasonable, the time constant for measurement cannot exceed 10 μs. In order to verify this theory, calculations were performed using Direct Monte Carlo Simulation [9–13]. The tablet was placed on chamber axis, on its bottom wall, while measurement sensor – on the upper wall, opposite of the tablet. The conducted calculations showed that when at initial moment there was vacuum in the chamber, the time required to reach measurement conditions was approx. 150 μs. The duration depends on the distance between tablet and sensor – thus it can be reduced by reducing the distance. While, if at the initial moment the chamber air at atmospheric pressure, even after 600 μs conditions were far from reaching steady state. Moreover, combustion product molecules that reached the sensor had energy corresponding to the energy of air in the chamber, which was a result of the fact that the molecules before reaching the sensor collided many times with air molecules.

Principles of measurement of energy emitted by ignition tablets

At the turn of 1950s and 1960s they were of interest among others due to the development of rocket technique, orbital flights, etc. Then a method for determination of heat flux under non-steady condition was developed – in shock tubes and devices based on them [14, 15], involving measurement of changes of surface temperature of wall of a

body under the flow. By treating measured temperature as a boundary condition for conductivity equation, one can determine abstracted heat flux in wall material. Before commencing numerical simulations, it was necessary to determine what type of gases and in what amount will be emitted as combustion products. To that end I used software *ICT – Thermodynamic – Code*. Detailed calculation assumptions and simulation results are presented in [16].

One dimension heat conductance equation for a general case has the following form

$$\rho \cdot c(\theta)\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}[k(\theta)\frac{\partial \theta}{\partial x}] \quad (1)$$

where: ρ – density; θ – temperature; $c(\theta)$ – specific heat; $k(\theta)$ – heat conductivity coefficient (temperature dependent); t – time; x – spatial coordinate.

This equation should be solved for initial and boundary condition:

$\theta(x,t) = 0$ for $t = 0$; $x > 0$

$\theta(x,t) = 0_w(t)$ for $t \geq 0$; $x = 0$

$\lim_{x \to +\infty} \theta(x,t) = 0$

The determined heat flux passing through plane x = 0 can be described using the following relation

$$\dot{q}(t) = -k(\theta)[\frac{\partial \theta(x,t)}{\partial x}]_{x=0} \quad (2)$$

Activating system

The activating system was constructed using resistance wire FeCrAl 135 of 0.13 mm diameter by Term Tech. This is a resistance material (equivalent of Kanthal D®, Resist Ohm135®) based on iron, chromium and aluminium of specific resistance ρ = 135 $\mu\Omega$/cm. Structure of FeCrAl wire makes it resistant to carbonizing and sulphated atmospheres. Figure 1 presents placement of activating system of measurement system during the conducted measurements.

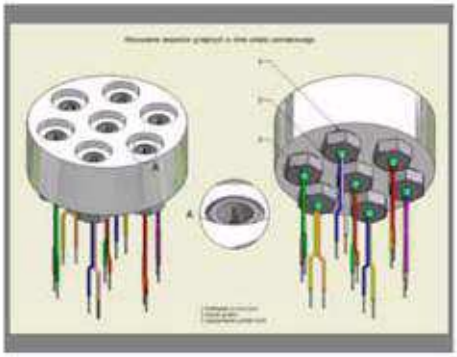

Fig. 1. Placement of activating systems

Measurement system

Fig. 2. Measurement station

1 – tablet press; 2 – heat measurement chamber; 3 – activation and ignition system; 4 – vacuum pump pipe; 5 – air compressor; 6 – data recording system

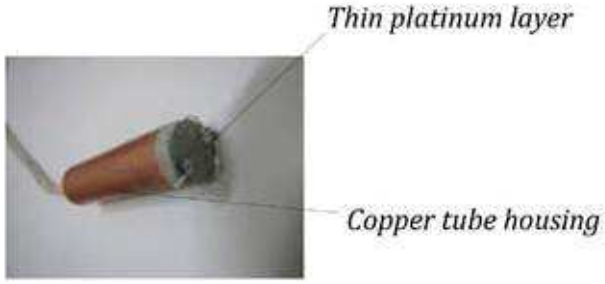

Fig. 3. Image of measurement sensor

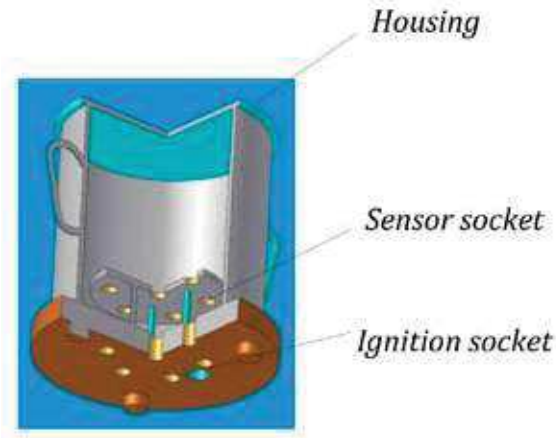

Fig. 4. Diagram of measuring system

Figure 4 presents fragments of apparatus used for measurement. Temperature measurement inside the chamber was done using platinum thermometer, made of glass plate with applied platinum path (Fig. 3). As the temperature increases, the resistance of measuring component increases linearly. Based on the measured resistance and knowing characteristic curve of the thermometer, temperature was measured. Recording device ESAM TRAVELLER was used for measurements with suitable software. The used platinum thermometers were made manually, each had slightly different resistance. This excluded application of one reference resistor for all the thermometers.

Test results

Figures 5 and 6 summarize results of conducted tests. Temperature change, heat flux and abstracted heat. Other test results are presented in [15].

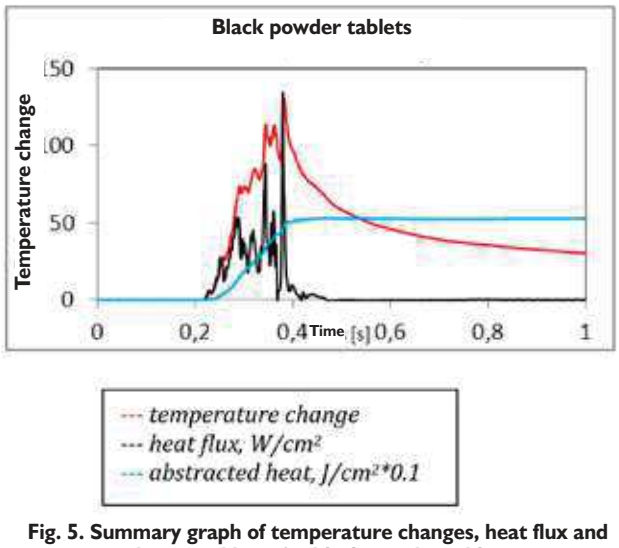

Fig. 5. Summary graph of temperature changes, heat flux and abstracted heat for black powder tablets

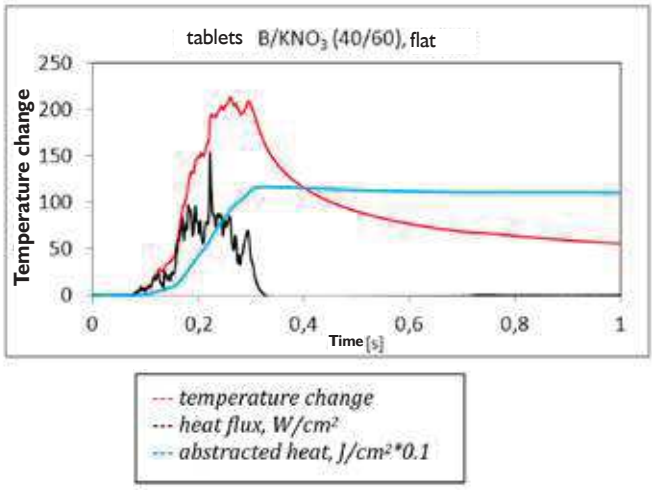

Fig. 6.Summary graph of temperature changes, heat flux and abstracted heat for "flat" B/KNO3 tablets

Additionally, after conducting heat tests, pressure pulses generated by pyrogenic mixtures were determined – using tests in ballistic chambers (Tab. 1).

Table 1

Measurement results of pressure peak for pyrogenic tablets

Tablet type	Composition	Geometry	Working time s	Abstracted heat J/cm²	Pulse, MPa*s
$BKNO_3$	Original	Convex	0.26	13.0	0.084
$BKNO_3$	40/60	Flat	0.25	12.7	0.041
$BKNO_3$	40/60	Convex	0.34	14.5	0.065
$Zr/KClO_4$	50/50	Flat	0.27	10.5	0.115
$Zr/KClO_4$	50/50	Convex	0.43	24.0	0.132
Zr/KNO_3	25/75	Flat	0.43	21.5	0.09
Zr/KNO_3	25/75	Convex	0.52	22.5	0.11
Zr/KNO_3	17/83	Flat	0.55	10.0	0.08
Zr/KNO_3	17/83	Convex	0.65	14.0	0.09
Black powder			0.25	5.5	

Conclusions

Prototype apparatus for measurement of effects during ignition of pyrogenic tablets. Application of more sensitive sensors (resistance thermometers) enabled recording temperature change on the sensor surface, while in-house software was used for determination of heat flux and total heat emitted by the tablets. Heat abstracted from the tablets varied in range 13 - 24 J/cm². According to the conducted analysis, optimum pyrogenic mixture is Zr/KNO_3 with 25:75 ratio providing long working time (0.55-0.65 s), high abstracted heat at level of 21 J/cm² and pressure pulse similar to B/KNO3 tablets. The obtained results were compared with classic ignition using black powder and working time was determined (0.25 s) and much lower abstracted heat (5.5 J/cm²).

Financial support from the State Committee for Scientific Research (KBN Project O N 508 004134) is gratefully acknowledged.

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