Express method to measure specific impulse of solid propellants

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Abstract
A new laboratory express method for determining the specific impulse of solid propellants based on the measurement of the reactive force of gasification products escaping from the propellant burning surface is presented in this work. The values of the specific impulse for a model composite solid propellant by varying the pressure in the combustion chamber are determined.

1. Introduction

The main energy characteristic of solid propellants (SPs) is the specific impulse of reactive force J_1 equal to the thrust increment on the expense of combustion of a unit mass of propellant. The value of J_1 in the absence of energy losses and in the condition of completion of chemical reactions is called the thermodynamic one. When the pressure in the nozzle exit section is equal to the external pressure, the thermodynamic value of the specific impulse is determined by the relation [1]

$$J_1 = \sqrt{\frac{2kRT_c}{k-1}\left(1-\frac{p_a}{p_c}\right)^{\frac{k-1}{k}}}, \qquad (1)$$

where R and k are the gas constant and adiabatic index of the combustion products, p_c and T_c are the pressure and temperature of the combustion products in the chamber, and p_a is the external pressure.
The computational-theoretical method for determining the thermodynamic specific impulse is implemented in the software (for example, Astra-4 [2]). For its implementation, it is necessary to specify the component composition of the SP or its equivalent formula, as well as the enthalpy of formation of the propellant components and the enthalpy of phase transitions, which are not always known for the new solid propellant compositions. It has to be underlined again that the values calculated in this way correspond to the maximum J_1estimate without taking into account any losses of the impulse.
The method for the direct experimental determination of the specific impulse is based on the measurement of thrust $P(t)$ and pressure $p_c(t)$ in the combustion chamber of a model rocket engine during combustion of the test SP sample. In this case, the value of J_1 can be determined from the ratio of the total thrust impulse during the engine operation time τ to the mass of the propellant consumed during this time [1]:

$$J_1 = \int_0^{\tau} P(t)\,dt \Big/ \int_0^{\tau} G(t)\,dt,$$

where $G(t)$ is the mass flow rate of the combustion products.
There is also a method for measuring specific impulses by using ballistic pendulum [3]. The impulse of the force acting on the pendulum during combustion of a SP sample in a rocket engine is proportional to the length of the deviation chord of the mass center of the pendulum from the equilibrium position. Disadvantages of the methods for direct measurement of specific impulses are the need to use model engines with a solid propellant charge weighing not less than 0.2–0.5 kg and the need for a special bench equipment placed in explosion-proof boxes.

Below, we present a laboratory express method for determining the specific impulse of SPs for propellant samples ~1–5 g in mass, which is based on the measurement of the reactive force *F* of gasification products escaping from the SP burning surface [4].

2. Experimental

To determine the specific impulse of tested SPs, a laboratory setup was developed (see Fig. 1) [5]. A cylindrical sample of the tested SP 1 with protection on the lateral surface 2 in the form of a quartz glass was horizontally mounted on the reactive force sensor 5 [6]. The capacitive sensor for measuring the reactive force of the combustion products escaping from the burning end surface of the sample was placed in the constant-volume bomb 3 mounted on the base 4. The electrical signal from the sensor 5 was passed through the signal–voltage electronic converter 6 and the analog-to-digital voltage converter 7 to the computer 8. Before the experiment, the constant-volume bomb was filled with an inert gas (nitrogen or argon) from the battery of cylinders 9 to a predetermined pressure, which was recorded by an reference manometer 10. Upon completion of the experiment, the combustion products of the SP sample were released through the valve 11.

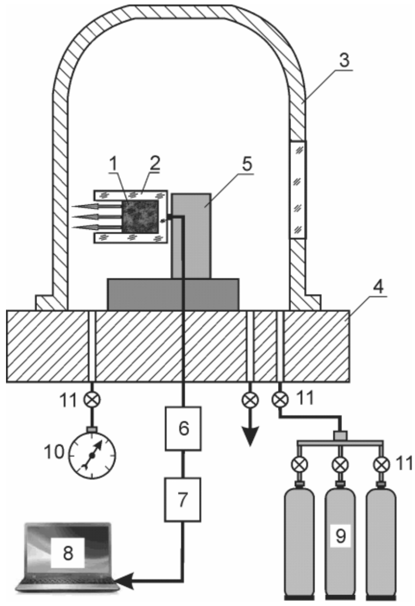

Figure 1: Laboratory setup for measuring the specific impulse: (1) SP sample; (2) quartz glass; (3) constant-volume bomb; (4) base; (5) reactive force sensor; (6) signal transducer; (7) analog-todigital converter; (8) PC; (9) battery of cylinders; (10) reference manometer; (11) valve

Before the experiment, the SP sample was weighed on an analytical balance (the error is ±0.01 g) and its height h_m and diameter d_m were measured. From these data, we calculated its density ρ_m and the area of the end burning surface *S*. The SP sample was ignited by an igniter composition at a fixed pressure p_c. In the process of combustion, we measured the reactive force *F* of the gasification products escaping from the end surface of the sample. The pressure was measured using an LKh-412 strain gauge (igniter and pressure sensor are not shown). The combustion time τ of the SP sample was determined from the pressure curve $p_c(t)$.
The reactive force of the gasification products is determined by the relation [4]

$$F = \rho u^2 S_m, \quad \textbf{(2)}$$

where ρ and u are the density and outflow rate of the gasification products. It follows from the law of conservation of mass that

$$\rho_m u_m = \rho u, \quad \textbf{(3)}$$

where u_m is the linear burning rate of the SP. From Eqs. (2) and (3) and the equation of state for an ideal gas $p_c = \rho R T_c$, we find the expression for the reactive force:

$$F = \frac{(\rho_m u_m)^2}{p_c} RT_c S_m .$$

Hence, now we can determine the complex RT_c (powder «strength» [3]), which is included in the equation for calculating the specific impulse:

$$RT_c = \frac{Fp_c}{S_m (\rho_m u_m)^2} . \quad \textbf{(4)}$$

The values of F, p_c, S, and ρ_m in Eq. (4) are directly measured in the experiment. The linear rate u_m is determined from the experimental data on the combustion time τ of a sample of known height h_m:

$$u_m = h_m / \tau . \quad \textbf{(5)}$$

After substituting Eqs. (4) and (5) in Eq. (1), the formula for calculating the specific impulse of the SP takes the form

$$J_1 = \frac{\tau}{\rho_m h_m} \sqrt{\frac{Fp_c}{S_m} \frac{2k}{k-1} \left(1 - \frac{p_a}{p_c}\right)^{\frac{k-1}{k}}} .$$

The value of the adiabatic index k is obtained from thermodynamic calculation or its average value is selected for SPs similar in composition ($k \approx 1.25$). This value is slightly changed by varying the initial component composition of the SP [1].

3. Results and discussion

The measurement of the specific impulse was carried out for a model SP composition comprising (by mass) of 81 % fine ammonium perchlorate, 14 % HTPB combustible binder, 1.5 % Alex aluminum nanopowder, 1.5 % iron oxide powder, and 2 % technological additives. The parameters of the SP samples are d = 10 mm, h_m = 20 mm, and ρ_m = 1.60 g/cm^3.

The results of determination of the specific impulse for three values of p_c averaged over five duplicate experiments are shown in Fig. 2. The relative measurement error of J_1 at a confidence probability of 0.95 does not exceed 3 %. The figure also presents the results of the thermodynamic calculation of J_1 using the Astra-4 software at p_a = 0.1 MPa (solid line). Analysis of the data shows that the calculated values of J_1 are 10–15 % higher than the measured values. This is due to the assumption that the chemical reactions are fully completed and the combustion occurs without heat losses. In the experiment, the response time of the gas-phase products in the protecting tube is finite and can be varied by changing the tube length. This allows one to simulate various conditions in combustion chambers of different sizes.

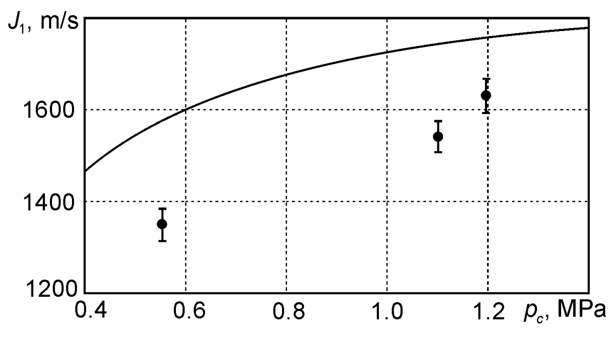

Figure 2: Specific impulse of the model SP depending on the pressure in the combustion chamber

4. Conclusions

Thus, it is experimentally demonstrated that the proposed method [5] makes it possible to determine the specific impulse of the SP in the laboratory conditions using small-sized equipment and low-mass samples (no more than 5 g).

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