MEASUREMENTS OF SPECIFIC IMPULSE OF SOLID ROCKET PROPELLANTS

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A new laboratory technique is presented for fast determination of the specific impulse of solid rocket propellants (SRPs), based on the measurement of recoil force of gasification products flowing from the burning surface of solid propellants. The values of specific impulse for the model composite solid propellant are obtained while varying the pressure in the combustion chamber.

Keywords: specific impulse; solid rocket propellant; gasification products; burning surface

Introduction

The main energy characteristics of SRPs is the specific impulse of force J_1 which is equal to the increment of thrust, being realized by the combustion of a unit mass of propellant. When considering the thermodynamic value of J_1, its specific impulse is determined in the absence of losses and complete chemical transformations. The thermodynamic value of the specific impulse with the pressure at the nozzle exit equal to the external pressure p_a is defined by the relationship [1]:

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

where R and k are the universal gas constant and the ratio of specific heats of the combustion products; and p_c and T_c are the pressure and temperature in the engine combustion chamber.

The theoretical calculation method for determining the thermodynamic specific impulse is implemented in various software codes (see, for example, "Astra-4" [2]). To implement this method, one should specify the composition of SRPs or its equivalent chemical formula, as well as the enthalpies of formation for fuel components and phase transitions which, in some cases, are unknown for new solid compositions. Furthermore, the calculated values of the specific impulse ignore incomplete combustion of the components of solid propellants and provide the upper estimate for J_1.

To model combustion of SRP test samples, the direct determination method based on the diagrams of thrust $P(t)$ and pressure $p_k(t)$ in the combustion chamber of rocket engine is usually used. The magnitude of J_1 is calculated as the ratio of the total thrust impulse during engine operation period and the mass of consumed propellant during this time [1]:

$$J_1 = \frac{\int\limits_0^\tau P(t)\,dt}{\int\limits_0^\tau G(t)\,dt}$$

where $G(t)$ is the mass flow rate of combustion products.

Another known technique for measurement of specific impulse is the ballistic pendulum [3]. Impulse of the force acting on the pendulum upon firing an SRP charge in a rocket engine is proportional to the length of the chord deflection center of mass of the pendulum from its equilibrium position. The disadvantages of direct methods for the measurements of the specific impulse is the need for model engines with solid propellant charge to weigh not less than 0.2–0.5 kg and the need for a special bench equipment placed in the explosion-proof boxes.

Measurement Technique

For determining the specific impulse of the investigated SRPs, the laboratory setup was developed (Fig. 1) [4]. Cylindrical sample of studied SRP *1* placed into quartz glass cup *2* was installed horizontally on the reactive force gage *5* [5]. Capacitance type gage for measuring the reactive force of combustion products flowing from the burning surface of the sample *1* of combustion products was housed in a constant volume bomb *3* installed on the base *4*. The electrical signal from the sensor *5* via the electronic signal converter *6* into a voltage and analog-to-digital converter voltage *7* into a digital code was fed to the recording personal computer *8*. Before the experiment, a constant volume bomb *3* was filled with inert gas (nitrogen or argon) from the battery of gas tanks *9* to a predetermined pressure which was recorded with a manometer *10*. After experiment, the SPR combustion products discharge was carried out through the valve *11*.

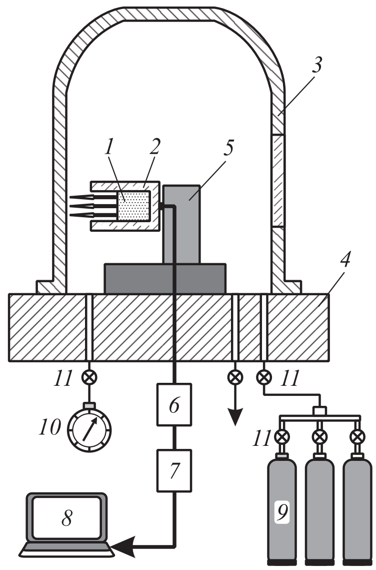

Figure 1 Scheme of the laboratory setup for measuring the specific impulse: *1* — sample SRP; *2* — quartz glass; *3* — bomb of constant volume; *4* — base; *5* — reactive force gage; *6* — signal converter; *7* — analog-to-digital converter; *8* — personal computer; *9* — battery of gas tanks; *10* — manometer; and *11* — valve

Before the conducting of experiment, a sample SRP was weighed on an analytical balance with an accuracy ±0.01 g and its height $h_{\rm pr}$ and diameter $d_{\rm pr}$ were measured. Based on these data, density $\rho_{\rm pr}$ and the area of the combustion surface $S_{\rm pr}$ were calculated. At a fixed pressure p_c, a sample SRP was ignited by the igniting composition. In the combustion process, the reactive force F of the gasification products flowing from the front surface of the burning sample was measured by sensor *5*. In addition, the burning time of the sample SRP τ was measured on the pressure diagram $p_c(t)$. Pressure was measured with a strain gage of LH-412 type (in Fig. 1, the pressure gage and igniter are not shown).

The value of reactive force of the gasification products is determined by [3]:

$$F = \rho u^2 S_{\rm pr} \tag{2}$$

where u and ρ are the density and outflow rate of gasification products.

From the law of conservation of mass, follows:

$$\rho_{\rm pr} u_{\rm pr} = \rho u \tag{3}$$

where $u_{\rm pr}$ is the linear burning rate of SRP.

From Eqs. (2) and (3) and the equation of state for an ideal gas

$$p_c = \rho R T_c \,,$$

the expression for reactive force can be got in the form

$$F = \frac{(\rho_{\rm pr} u_{\rm pr})^2}{p_c} R T_c S_{\rm pr} \,.$$

From here, one can define the complex (RT_c) — "the powder force" [3], which is included in the equation for the calculation of the specific impulse

$$R T_c = \frac{F p_c}{S_{\rm pr} (\rho_{\rm pr} u_{\rm pr})^2} \,. \tag{4}$$

All parameters in expression (4) are directly measured in the experiment (F, p_c, $\rho_{\rm pr}$, $S_{\rm pr}$). Linear burning rate of SRP is also determined experimentally through the combustion time τ of a sample of the known height $h_{\rm pr}$:

$$u_{\rm pr} = \frac{h_{\rm pr}}{\tau} \,. \tag{5}$$

Substituting (4) and (5) in (1), one obtains the formula for calculating the value of specific impulse of SRP:

$$J_1 = \frac{\tau}{\rho_{\rm pr} h_{\rm pr}} \sqrt{\frac{F p_c}{S_{\rm pr}} \frac{2k}{k-1} \left(1 - \frac{p_a}{p_c}\right)^{(k-1)/k}} \,.$$

The value of the adiabatic index k is taken from the thermodynamic calculation or its average value is selected for similar composition of SRPs ($k \approx 1.25$). This value varies slightly when varying the initial component of SRPs [1].

Thus, it is shown experimentally that the proposed method [4] allows for the laboratory determination of the specific impulse of SRPs using compact equipment and samples of low mass (not more than 5 g).

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