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Experimental investigation of the factors affecting the burning rate of solid rocket propellants

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HIGHLIGHTS

- Burning rate in a rocket motor is an important factor determining the rocket performance.
- Burning rate is the most important design criteria for the solid propellant rockets.
- Initial temperature of the solid propellants affects the working performance of the rocket.
- Adding Al into the ingredient of DB propellant increases the burning rate and energy.
- The results based on DB ingredients adding Al shows similarities with the literature.

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ABSTRACT

The burning rate of the solid rocket propellants is one of the most important factors that determine the performance of the rocket. The burning rate of rocket motors running with solid propellant is called flame regression, which occurs with the ignition in the fuel grain perpendicular to the burning surface. This study investigates the effects of the addition of metal-based high-energy matter (Aluminum) into the content of the propellant produced within the scope of development project. The study starts with the manufacture of propellant samples. For the data input in the burning rate measurement device, the determination process of energy levels of the manufactured propellant samples with a calorimeter is performed. Then, the other data related to the propellants to be measured for the burning rate, such as energy level of the propellant, the propellant density, the maximum combustion temperature, and the physical sizes of the propellants, were inputted to the computer of the burning rate measurement device. The 22 g of the sample propellant to be measured for burning rate was placed in a part of the burning rate measurement device, "closed bomb" which has a capacity of 200 cm^3. Burning rate measurements were performed at the same time in a constant-volume environment under different pressures. The burning rate of the double base propellant without aluminum (DB-1) was compared with other double base fuels in which aluminum was added by 2% (DB-2) and 4% (DB-3). It was found that the burning rates and burning heat of new fuels manufactured by adding aluminum to the content of the standard double base fuel (DB-1) increased.

1. Introduction

One of the most important design criteria of rockets running with solid propellants is the burning rate of the solid propellant. For this reason, the burning rate of the propellant which will be used in rocket motor design initially must be known. The burning rate of a solid propellant is expressed as the regression of propellant perpendicularly from the center of the nucleus. The burning rate of the solid propellants varies depending on many factors, such as the combustion chamber pressure, the initial temperature of solid propellant before the ignition, the percentage of high-energy matters in the propellant content, the burn sensation of the flammable substance, the additional chemical substances regulating the burning rate, and the percentage of the amount of oxidizing agent.

Although the burning event of the solid rocket propellants is quite complex, its mathematical model is sufficiently established.

Abbreviations: DB, double base; NG, nitroglycerin; NC, nitrocellulose; CMDB, composite solid propellant; PbSa, lead salicylate; PbEH, lead two ethyl hexanoat; UT, ultrasonic burning rate measurement technique; SBT, strand burner burning rate measurement technique; AP, ammonium perchlorate; IPDI, isophorone diisocyanate cured; DEP, diethyl phthalate; NG, nitroglycerine; 2NDPA, 2Nitrodiphenylamine.

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Burning which starts from the nucleus in motors of the solid rocket propellant progresses in a direction perpendicular to the outside surface of the propellant. As the burning progresses perpendicularly, the viscosity of the propellant lessens. The amount of reduction in the thickness of the propellant per unit of time is expressed as the burning rate. In military applications and cabinet in space research, the rocket motor sends the warhead to the intended destination. In the design of the rocket engine, the specific impulse (I_{sp}), the burning rate (r), the propellant density (ρ_b), the combustion chamber pressure (P_c), the intended thrust force (F), the maximum engine pipe diameter (D), the burning surface area (A_b), the nozzle cross-sectional area (A_t), and the total mass of the engine should be determined carefully [1,2].

The mathematical representation of burning rate of solid rocket propellant and factors affecting burning rate is given by

$$\text{Linear Burning Rate} = \frac{\text{Solid Propellant (mm)}}{\text{Burning Duration (s)}} \tag{1}$$

$$r = \frac{dw}{dt} \tag{2}$$

The solid propellant burning rate equation known as Vielle's Law is

$$r = kP_c^n \tag{3}$$

The burning rate (r) essentially depends on the initial temperature of propellant and pressure of the combustion chamber. P_c combustion chamber pressure, k initial constant temperature of the solid and its value vary between 0.002 and 0.05, n which is called as the pressure index or pressure base is a function of the solid propellant formulation. In double base (DB) propellants, the value of n is between 0.2 and 0.5 and in AP (Ammonium Perchlorate) based composite fuels, the value of n is relatively lower, varying from 0.1 to 0.4 [4].

During development of a new or modified solid propellant, it is extensively or characterized. This includes the testing of the burning rate (in several different ways), under different temperatures, pressures, impurities, and conditions. Characterization also requires measurement of physical, chemical, manufacturing properties, ignitability, aging, sensitivity to various energy inputs or moisture absorption and compatibility with other materials. It is a lengthy, expensive, often hazardous program with many test, samples and analyses [9].

The burning rate of propellant in a motor is a function of many parameters and at any instant governs the mass flow rate $\dot{m}$ of hot gas generated and flowing from the motor (steady combustion):

$$\dot{m} = A_b r \rho_b \tag{4}$$

Here (A_b) is the burning the burning area of the propellant grain, (r) the burning rate, and (ρ_b) the solid propellant density prior to motor start. The total mass (m) of effective propellant burned can be determined by integrating equation:

$$m = \int \dot{m}dt = \rho_b \int A_b r dt \tag{5}$$

where (A_b) and (r) vary with time and pressure [9].

The initial temperature of solid propellant directly affects the combustion chamber pressure (P_c) and burning rate (r). This effect is expressed as the burning rate temperature sensitivity (Π_r) and the equation of burning rate change under constant pressure with different temperatures is as given below;

$$\Pi_r = \left[\frac{\partial r}{\partial T}\right]_{P_c} = \left[\frac{\partial \ln(r)}{\partial T}\right]_{P_c} = \left[\frac{\partial \ln(kP_c^n)}{\partial T}\right] = \frac{1}{k}\left[\frac{\partial k}{\partial T}\right]_{P_c} \tag{6}$$

The temperature sensitivity of the pressure (Π_P), burning surface and nozzle block section ratio in fixed conditions is expressed with the following equation [3,5];

$$\Pi_P = \frac{1}{P_c}\left[\frac{\partial P_c}{\partial T}\right]_{\frac{A_b}{A_t}} = \left[\frac{\partial \ln P_c}{\partial T}\right]_{\frac{A_b}{A_t}} \tag{7}$$

From the above equation;

$$\Pi_P = \frac{\partial \ln(P_c)}{\partial T} = \left(\frac{1}{1-n}\right)\frac{1}{k}\left[\frac{\partial k}{\partial T}\right] = \frac{\Pi_r}{1-n} \tag{8}$$

The equations of (1)–(8) given above correlate with the temperature, the pressure, and the burning rate.

There are many parameters affecting the burning rate in solid propellants. First is the combustion chamber pressure of rocket motor (Pc). The chemical structure of the propellant, the rate of propellant in the fuel, and particle size of propellant components are known as the effective structures on the burning rate of solid propellant. The initial temperature of solid rocket propellant before the ignition directly affects the burning rate, burning time, and internal engine pressure.

1.1. Burning in solid propellants

In motors running with solid propellant, the burning event is quite complex. The chemical and physical events happening during the burning are not fully understood. Burning models developed so far are still quite simplified. The flame structure, gaseous phases, and other products during the burning can only be demonstrated with mathematical models [2,6].

The burning rate in rocket motors running with solid propellants is expressed as a regression from the combustion surface in terms of time. As seen in Fig. 1, the burning rate of solid propellants can be accepted as the burning distance per unit of time. Generally, mm/s, cm/s and inch/s are used as the units of burning rate.

In DB fuels, burning happens without a need for oxygen due to the co-existence of propellant (NG and NC), which are fundamental components of DB fuels.

In composite solid propellants used in modern solid propellant rocket motors, AP, polymer-based binder, and powdered aluminum (Al, between 0% and 20% amount) are generally used as oxidizers [6]. The use of metallic fuel has a modulating effect on unsteady burning in low pressures. In addition, it is known to increase the specific impulse of rockets. But on the other hand, it decreases the temperatures and rates of burning products leaving the nozzle, due to the aluminum oxide formation. The mixing ratios of solid rocket propellants by weight in general are given in Table 1 below.

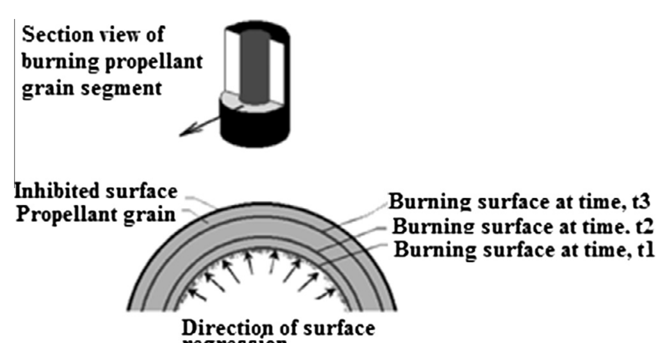

Fig. 1. Burning rate regression of solid propellant from the nucleus of the fuel to the outer surface of rocket motor in a perpendicular direction in terms of time [7].