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Burning rate of AP/HTPB base-bleed composite propellant under free ambient pressure

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ABSTRACT

Base bleed is an important extended-range technology wherein low-speed mass flux is injected with high temperature by using an ammonium perchlorate (AP)-based burning composite propellant. The range of a projectile can be increased effectively by controlling the burning rate of the propellant. In this study, the burning rate of a type of bimodal AP/hydroxyl-terminated polybutadiene (HTPB) base-bleed composite propellant was measured under ground free ambient pressure (0.99 atm) by using laser ignition, high-speed video, and image-processing technology. As it is difficult to determine the existing burning rate of this bimodal AP/HTPB base-bleed composite propellant, a numerical calculation model of the burning rate was constructed. The numerical calculation result, that is, 1.59 mm/s, agrees well with the experimental value of 1.607 mm/s.

1. Introduction

The firing ranges and impact precisions of new weapons systems are expected to be constantly improved [1]. Notably, among the three components of the drag affecting a projectile, the base drag frequently accounts for one-half, or even much more, of the total drag for large caliber ammunitions [2]. Reducing the base drag is effective in reducing the total drag. Base bleed is an extended-range technology that is developed by injecting low-speed mass into the base region to reduce the base drag, and was first suggested many years ago by Baker et al. [3]. A system's firing range is extended 20%–30% by reducing up to 70% base drag with the base-bleed technique [4,5]; however, the precision decreases greatly and the range dispersion is much bigger than a conventional projectile. The major factor causing the range dispersion of a base-bleed projectile is the burning inconsistency of the base-bleed unit [6].

In fact, the mass flow rate injected in the base of projectile is in the form of a high-temperature gas obtained by burning a type of base-bleed solid propellant, whose burning rate is approximately 1–3 mm/s [7] or even <1 mm/s [8]. The solid propellant is contained in a combustion chamber located at the base of the projectile. A hole is different from a nozzle, such as that found in a rocket-assisted projectile, to minimize the thrust resulting from the burning propellant. Fig. 1 illustrates the significant difference

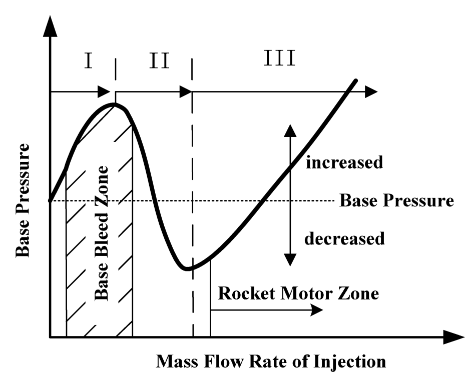

Fig. 1. Base pressure versus mass flow rate and the effect regime on base bleed.

between the work principles of a base-bleed unit and a rocket motor. This clearly demonstrates the base pressure is affected by the injection mass flow rate [4]. As the base-bleed propellant burns mainly under lower pressure, it is very important to study the combustion mechanism and properties under free ambient pressure (Fig. 1).

Ammonium perchlorate (AP)-based and hydroxyl-terminated polybutadiene (HTPB) composite propellants are used extensively in rocket motors, and numerous experimental and theoretical studies have been conducted on their combustion mechanisms [9–11]. An AP/HTPB composite propellant is an important type of base-bleed propellant used in many base-bleed-extended projectiles, and is a mixture in which crystalline AP/HTPB serves as an oxi-

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Fig. 2. Samples AP/HTPB base-bleed composite propellant.

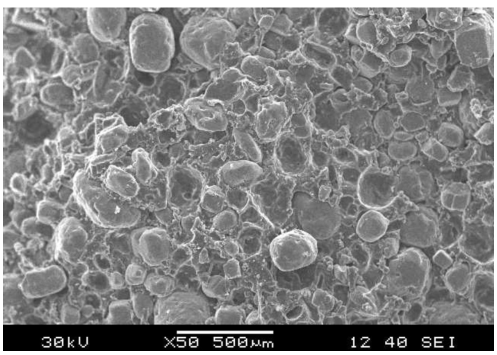

Fig. 3. SEM image of AP/HTPB base-bleed composite propellant. The sizes of coarse and fine particles are 180 μm (65%) and 100 μm (35%), respectively.

dizer and fuel binder. The physical structure of AP/HTPB composite propellants is heterogeneous; thus, its combustion wave structure is heterogeneous. Hence, the combustion of composite propellant involves intricate physical–chemical processes [12,13].

The remainder of this paper is organized as follows. Section 2 demonstrates the measurement of the burning rate of the AP/HTPB base-bleed composite propellant by using laser ignition, high speed video, and image processing technology under free ground ambient pressure. Further, Section 3 describes the construction of a burning-rate calculated model for bimodal AP/HTPB composite propellant according to the heat balance equation of combustion. Section 4 provides an example of the calculation of the burning rate of AP/HTPB base-bleed composite propellant. Finally, in Section 5, some conclusions were drawn from the research results.

2. Experimental methods

The burning rate was measured under free ground ambient pressure. The propellant samples consist of 78% AP and 22% HTPB, which were taken from a 155 mm caliber base-bleed propellant grain. The shape of samples used in this study was approximately 3 mm × 3 mm in cross section and 20 mm in length, as shown in Fig. 2. The propellant is bimodal AP composed of coarse particles ($D_c = 180$ μm, weight ratio = 65%) and fine particles ($D_c = 100$ μm, weight ratio = 35%), which were obtained from the scanning electron microscopy (SEM) image, as shown in Fig. 3. It is known that the burning rate of AP-based solid propellants has a strong relationship with the initial temperature of the propellant [14–16]. Hence, the samples were stored in an incubator at 15 °C for more than 24 h to eliminate the influence of the initial temperature on the burning rate. The ground free ambient pressure is 0.99 atm, with no wind.

The strand burner equipped with a hot wire or plate has been consistently used as an igniter to measure the burning rate of a propellant in several studies [17]. However, the laser ignition technology (CO_2 laser device, SYNRAD_F201, 200 W, USA) was used in this study because of its high energy intensity and the high accuracy of the measured, controlled, and reproduced energy flux [18,19]. A high-speed video system was used to capture the highly clear images of the burning process. An oscilloscope was used to record the start time of the laser, and a synchronous trigger device was used for simultaneously starting the laser device and high-speed video. Fig. 4 shows the experimental setup for measuring the burning rate. Furthermore, Fig. 5 illustrates the series of combustion images of the sample tested and recorded by high-speed video.

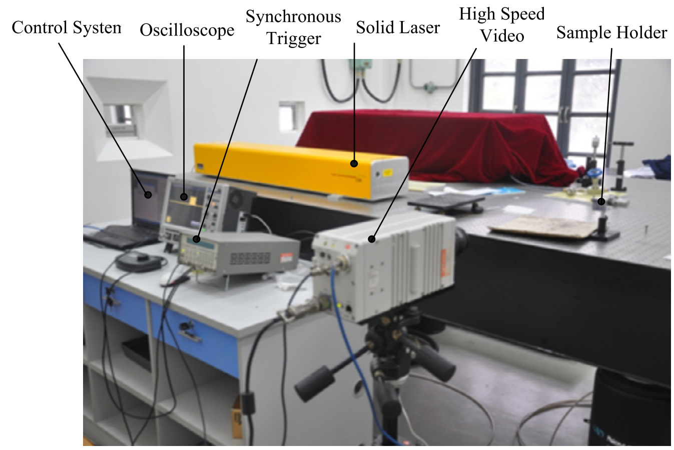

Fig. 4. Experimental setup of measuring the burning rate of AP/HTPB base-bleed composite propellant. The system is mainly based on the laser ignition system and high-speed video.

The burning rate was calculated by

$$r = \frac{(l_1 - l_2)}{(t_2 - t_1)} \cdot \frac{D}{D'} \tag{1}$$

where r is the linear burning rate (in mm/s); l_1 and l_2 are the non-burning lengths of the sample in image pixels at times t_1 and t_2, respectively; and D and D' are the real length and image lengths in millimeter and pixels, respectively.

The experiment was conducted under four levels of laser energy intensity: 4.5, 7.5, 14.99, and 22.61 W. Table 1 lists the experimental data.

3. Burning-rate model

The combustion of AP/HTPB composite propellants and measurement of their burning rates have been extensively studied. A literature review on analytic and experimental studies of AP-based composite combustion was presented by Murthy et al. [20]. Moreover, the multiflame model (the Beckstead–Derr–Price model) by Beckstead et al. [9] detailed the finite-rate chemical kinetics model considering both gaseous and condensed phases by Cai [12] and the erosive burning model that refers to the cross-flow enhancing effect [21,22]. Numerous research results have shown that the AP reaction is a dominant factor because of higher percent mass loading and being more chemically active than HTPB. Moreover, the particle size of AP is much smaller and the burning rate is much higher. Therefore, although numerous informative results of the burning rate of AP-based propellants have been reported, they differed greatly because of the difference in experimental pressure conditions, such as ingredients, particle size of AP, initial temperature, and catalysts [23–26]. Fig. 6 illustrates some important results, from which it is difficult to infer the exact burning rate value under free ground ambience condition.