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Ignition theory investigation and experimental research on hybrid rocket motor

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ABSTRACT

A transient ignition model is established based on the theoretical analysis of hybrid rocket motor ignition process. The ignition process can be divided into four stages: inert heating, ignition, flame propagation, and rapid pressure buildup. The inert heating up time takes up the main part of the ignition delay. An experiment system is designed for 90% hydrogen peroxide laboratory-scale hybrid rocket motor with catalytic ignition. Firing tests are carried out with polymethyl methacrylate (PMMA) and polyethylene (PE) fuels. The ignition criteria of 90% H_2O_2/PE hybrid rocket motor are established by comparing the theoretical calculations with experimental results. Comparison results show that the ignition process is governed by both the temperature criterion (TC) and the oxidizer-to-fuel ratio criterion (OFC). OFC determines ignition delay at a low oxidizer mass flux and TC determines ignition delay at a higher mass flux. In addition, the ignition delay time is more sensitive to the initial oxidizer temperature than the initial fuel temperature.

1. Introduction

Hybrid rocket motors use liquid oxidizer and solid fuel as propellants. They have advantages such as safety, low cost, throttling and multiple restart capabilities. The hybrid rocket motor presents extensive application prospects in the fields of sounding rocket, launch boost, small satellite propulsion system, and manned spaceship. Ignition technology is an essential aspect to realize the advantages of hybrid rocket motors.

Available liquid oxidizers and solid fuels for hybrid rocket motors are extensive. Low toxicity and pollution are important characteristics for future propulsion concepts. For example, nitrous oxide (N_2O) and hydrogen peroxide (H_2O_2) are two kinds of widely used oxidizers for hybrid rocket motors. A large number of researches have been conducted on the ignition technologies for hybrid rocket motors using such fuels.

Various ignition systems were built up for the N_2O hybrid rocket motors. Eilers et al. [6] used one of two small solid ammonium nitrate/magnesium rockets imbedded in the motor injector cap to ignite the N_2O/hydroxyl terminated polybutadiene (HTPB) motor. Arves et al. [1] utilized a safe non-pyrophoric/non-pyrotechnic ignition system to maintain the non-explosive/non-hazardous rating of the N_2O/HTPB hybrid vehicle. In research on diaphragm effects of N_2O/paraffin hybrid rocket motor by Grosse [7], ignition was achieved by a 10–14 g piece of AP/HTPB composite propellant which was initiated by a small commercial squib. Shan et al. [14] and Wan et al. [16] developed an igniter based on the catalytic decomposition of N_2O for a laboratory-scale polymethyl methacrylate (PMMA)/HTPB hybrid rocket motor.

Catalytic ignition is one of the most popular methods for the H_2O_2 hybrid rocket motor. In Wernimont et al. [17,18], a consumable catalytic bed (CCB) design was used to provide rapid, reproducible ignition using stabilized H_2O_2. The CCB was inserted into a pocket which was machined into the forward end of the fuel grain. Based on this investigation, Austin et al. [2] conducted studies of variable thrust, multiple start hybrid rocket motor solutions. To add multiple-start capability to a hybrid rocket motor without reliance on a catalyst bed or torch ignition system, an entire catalytic fuel grain with the oxidizer was introduced. Nine fuel formulations were developed in order to assess reactivity with 90% H_2O_2. Some of the formulations achieved smooth ignition and high regression rate performances. Du [5] and Zhang [19] et al. conducted experimental research of 85% H_2O_2/polyethylene (PE) hybrid rocket motor using a silver plated nickel screen catalytic bed. The results showed that the ignition delay was longer than 5 s. Song et al. [15] developed an igniter based on the catalytic decomposition of H_2O_2 and RP-1 fuel. In their research, the combustion flame of the igniter was used to ignite the H_2O_2/HTPB hybrid rocket motor. The

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combustion gas temperature of the igniter exceeded 2000 K, which was significantly higher than 1000 K of the catalytic decomposition products of 90% H_2O_2. The results indicated that the ignition delay was decreased by using this igniter.

To the best of the authors' knowledge, most of the previous researches focused on the realization of the rapid and stable ignition, but researches of ignition theory and transient model of hybrid rocket motor were less discussed. The ignition model is the foundation of investigating the ignition technology. Developing an ignition criterion is the essence of analyzing the ignition influencing factors of the hybrid rocket motor.

This paper describes the characteristics of the hybrid rocket motor ignition process. An ignition model of the hybrid rocket motor is developed based on the ignition theory studies. With the H_2O_2 hybrid rocket motor, theoretical analyses and experimental studies are conducted about the catalytic ignition process. Ignition criteria are established and analyzed. Influences of initial temperature on the ignition delay are investigated. Quantized ignition criteria provide an approach for further researches of the hybrid rocket motor ignition technology.

2. Ignition process analysis

In the non-catalytic hybrid rocket motor, the ignition system is usually activated firstly to provide a heat source to initiate the gasification of the solid fuel. The oxidizer spraying into the combustion chamber is also heated by the igniter. For the catalytic ignition method, the oxidizer is decomposed in a catalyst bed and decomposition products provide heat for the fuel pyrolysis. The gasified oxidizer and pyrolyzed fuel mix together with each other. When the ignition conditions are reached, the combustion flame of the main flow develops and propagates downstream quickly. The combustion flame provides required heat to ignite the motor completely. Then the oxidizer and the fuel react with each other in a stable working state.

The ignition process of the hybrid rocket motor can be divided into four stages.

(1) Inert heating

This stage starts from the activation of the motor until the developing of the combustion flame in the fuel port. In this stage, the solid fuel is heated from the initial temperature to the pyrolysis point by igniter gases or oxidizer decomposition products. The duration of this stage is defined as the inert heating up time τ_1, which takes up the major part of the entire ignition delay time.

(2) Ignition

This stage is the demarcation point of the first and third stages. After the temperature of the fuel surface reaches the pyrolysis temperature, the pyrolyzed fuel will be blown off by the oxidizer and they mix with each other. Under certain conditions, a flame will form in the fuel port. The emphasis of this stage is to establish conditions or criteria in which the oxidizer and pyrolyzed fuel ignite. Therefore, the duration time of this stage can be considered to be zero for this model.

(3) Flame propagation

After igniting the oxidizer and fuel in the fuel port, the flame propagates into the entire combustion chamber. However, the flame propagation velocity is usually very fast and the combustion chamber pressure does not change obviously in time. The flame propagation time of this stage is defined as τ_3.

(4) Rapid pressure buildup

When the flame fills the entire fuel port, more heat is conducted to the fuel compared with the first inert heating up stage. The pyrolysis rate of the fuel increases with the increasing fuel surface temperature. This causes the reactions to accelerate, which provide sufficient heat for sustaining the fuel heating and pyrolysis in turn. At the same time, the "blowing effect" of the fuel pyrolysis in the boundary layer blocks the heat transfer from flame to fuel surface, which decreases the convective heat transfer coefficient. As a result, the heat transfer will eventually reach a balance. At this stage, the mass flow rate of the propellants gradually increases due to the addition of the fuel. Therefore, the combustion chamber pressure rises correspondingly. Stabilization of the combustion chamber pressure indicates the end of rapid pressure buildup stage. The duration of this stage is called as τ_4.

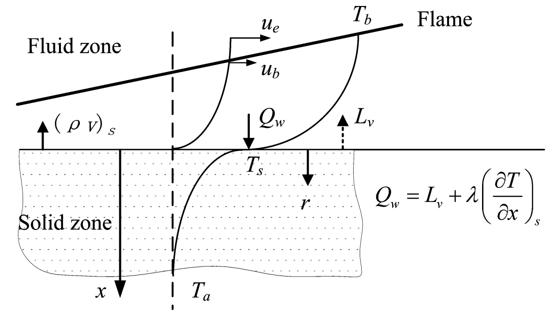

Fig. 1. Thermal transient state of the solid fuel.

Therefore, the ignition delay time of the motor can be described as follows:

$$\tau_t = \tau_1 + \tau_3 + \tau_4 \tag{1}$$

The mechanism of each stage of the entire ignition process is different. Because of the diffusion combustion characteristic of hybrid rocket motors, the main transient processes affecting the ignition are thermal transient of the solid fuel, diffusion and combustion of the boundary layer, and pressure buildup of the combustion chamber.

3. Transient model

3.1. Thermal transient model of the solid fuel

Fig. 1 shows the thermal transient process in the solid fuel. The hypotheses used in this paper are: (1) the fuel layer is thick enough that the inner temperature of the fuel is the same as the environment temperature; (2) the radius of the fuel port is large enough that the panel model can be used for the convective heat transfer of the fuel surface; (3) the process of fuel pyrolysis occurs in a very thin layer near the fuel surface, and the thickness of this layer can be neglected; (4) thermal properties of the fuel are constants, such as the specific heat and the thermal diffusion coefficient; (5) the temperature gradient in the axial direction is much lower than that of the radial direction. Therefore, in the coordinate system established on the moving fuel surface, the thermal diffusion equation can be expressed in the form of the semi-infinite panel model as follows (see [8]):

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} + \dot{r}(t)\frac{\partial T}{\partial x} \tag{2}$$

where κ is the thermal diffusion coefficient, T is the temperature, and $\dot{r}(t)$ is the fuel regression rate.

For the semi-infinite zone problem, the boundary condition of the far field can be expressed by Dirichlet or Neumann type, that is

$$x \to \infty: \quad T = T_a \quad \text{or} \quad \frac{\partial T}{\partial x} = 0 \tag{3}$$

The second boundary condition at the surface near the flow field can be derived from the energy conservation equation as follows: