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Defence Technology 12 (2016) 96–100

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Mechanism of plasma ignition in electrothermal-chemical launcher

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Received 29 September 2015; revised 28 December 2015; accepted 28 December 2015

Available online 28 January 2016

Abstract

Plasma generator is a core component in an electrothermal-chemical (ETC) launcher. Its work state directly influences the launch efficiency of a system. The interaction between plasma and propellants is a very important mechanism in ETC technology. Based on the transient radiation model and open air plasma jet experiment, the mechanism of plasma ignition process is analyzed. Results show that the surface temperature of local solid propellant grain can quickly achieve the ignition temperature under the action of early transient plasma radiation. But it needs enough time to maintain the high energy flow to make self-sustained combustion of solid propellant grains. Because of the limited space characteristics of transient radiation, the near-field propellant grains can gain enough energy by the strong transient radiation to be ignited and achieve self-sustained combustion. The far-field propellant grains mainly gain the energy by the activated particles in plasma jet to be ignited and self-sustained combustion. Experiments show that plasma jet always has a high flow velocity in the area of the cartridge. Compared with conventional ignition, the solid propellant grains can obtain more quick and uniform ignition and self-sustained combustion by this kind of ablation controlled arc (ACA) plasma via energy skin effect of propellant grains, pre-heat temperature mechanism and high efficient jet diffusion.

Keyword: Electrothermal-chemical launch; Plasma ignition; Transient radiation; Plasma jet

1. Introduction

Electrothermal-chemical (ETC) launch can be used to obtain more smooth interior ballistic process and improve the kinetic energy (KE) of the projectile relative to the conventional ballistics [1]. Capillary structure is always designed and used as the ablation material to support the ablation controlled arc (ACA) plasma in ETC launchers [2]. The features of an ACA hybrid plasma jet can be controlled and regulated accurately by the discharge parameters of a pulse power supply (PPS) [3]. This kind of high temperature transient plasma has a great advantage to improve the ignition and combustion of solid propellants compared with conventional ignition using energetic materials, such as black powder. Optimizing the structural design and work parameters of plasma generator is of considerable significance in engineering applications.

The previous calculations and experiments show that the plasma temperatures ranged from 0.35 eV (4000 K) to 3 eV (35,000 K) [4,5]. At the moment when plasma is injected into a propellant bed, energy is transferred rapidly to the propellant grains nearby the plasma generator via instantaneous radiation, which might lead to ignition. There must be a strong radiation that may be used to optimize the ignition and combustion processes. After ignition, the plasma radiation is damped quickly through the high pressure gas produced by propellant burning. Energy is transferred quickly to the propellant grains far from the plasma generator via plasma jet diffusion.

Lots of works in theory and experiments have been done to investigate the plasma–propellant interaction, and the enhancement function of plasma has been proven by experiments. But the mechanisms of plasma ignition and enhancement in the ETC launch process have yet been understood clearly. In this paper, a transient radiation model and relevant plasma jet experiments are established to discuss and help to understand the mechanism of plasma ignition in the ETC launch process from the view of radiation and diffusion, respectively.

2. Near-field: radiation

In our previous works [6,7], a Monte Carlo method was employed in an attempt to understand the characteristics of plasma and its interaction with propellant grains by the transient radiation at the moment of discharging. A three-dimensional model was established to simulate the early transient radiation in cartridge based on the model in Ref. [6]. All

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Peer review under responsibility of China Ordnance Society.

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http://dx.doi.org/10.1016/j.dt.2015.12.009

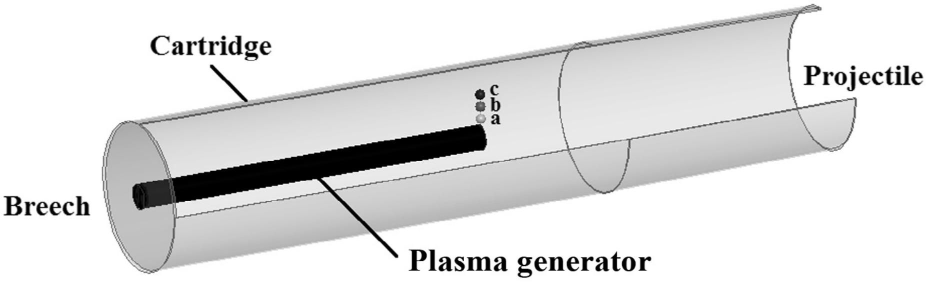

Fig. 1. Schematic diagram of 3D radiation model.

propellant grains are uniformly aligned around the serial arc plasma generator in the center of the cartridge, as shown in Fig. 1, and are characterized by a porosity P and an average absorption coefficient α. Here $P = V_p/V$, where V_p is the volume of propellant and V is the volume of cartridge.

The assumptions here are as the same as those in Ref. [6]. Plasma is a graybody radiator, and the radiant energy E_b is

$$E_b = \varepsilon\sigma T^4 \tag{1}$$

where ε is the emissivity; σ is the Stefan–Boltzmann constant; and T is the plasma temperature. The temperature inside the plasma generator is assumed to be finite and constant. In our calculations, T is assumed as 30,000 K. The radiant energy consists of n energy beams, and each energy beam has an energy E given by

$$E = E_b / n = \varepsilon\sigma T^4 / n \tag{2}$$

We also assume that the radiation and absorption of propellant grains follow Kirchhoff's law based on local thermodynamic equilibrium (LTE) conditions [8]. The propellants are assumed to be spherical and have diffuse reflective surfaces. Their quantum absorption ΔE_p is

$$\Delta E_p = \alpha \cdot E = \alpha \cdot \varepsilon\sigma T^4 / n \tag{3}$$

where α is the average absorption coefficient. We also assume that the scattering direction of the energy beam is random. And the wall of cartridge is assumed to have the same absorption characteristics as the propellant grains.

The gases in the cartridge are assumed to behave as optical film and also are supposed to be in thermodynamic equilibrium (TE) with the attenuation to the energy beam E' described as

$$E' = E \cdot \exp(-\beta s) \tag{4}$$

where s is the length of the path and β is the attenuation coefficient of the gases in cartridge. β is assumed to be 0.01 in the calculations.

We also assume that all of the energy absorbed by the propellant grains is used to increase their surface temperatures.

The three-dimensional radiation model is coupled with a thermal model shown in Fig. 2 to predict the surface temperature of propellant grains and the distribution of temperature in the cartridge. It is reasonable to assume that the radiative heat transfer from the plasma source to the surfaces of propellant grains is extremely efficient in a strong instantaneous radiation. Hence, the heat transfer from the surface of propellant grain to its interior is relatively slow.

The surface layer of propellant grains can be defined as the area in the dashed boundary in Fig. 2, and the boundary of its surface layer is approximated as an adiabatic boundary.

The surface temperature of the ith propellant grain can be written as

$$T_{si} = T_0 + \Delta T_i = T_0 + q_i \cdot \Delta t \big/ \left(m \cdot k \cdot C_p + \lambda \cdot \Delta t / r\right) \tag{5}$$

where q_i is the energy flux reaching the surface of the propellant grain, as calculated by the radiation model; T_0 is the initial temperature of propellant grains (288.15 K); C_p and λ are the specific heat at constant pressure and the thermal conductivity of propellant grain, respectively; m is the mass of propellant grain, $m = 5.149$ g; Δt is the actual time of radiation; and k is the volume ratio of surface layer to propellant grain. Based on the parameters of JA2 [9], C_p and λ of propellant grains are selected as 1520.45 J/(kg K) and 0.28 W/(m K), respectively. For a spherical particle, we have

$$k = \left(3R^2 - 3R + 1\right) \big/ R^3 \tag{6}$$

where R is the ratio of the surface layer thickness to the radius of propellant grain. The radius of propellant grain is on the

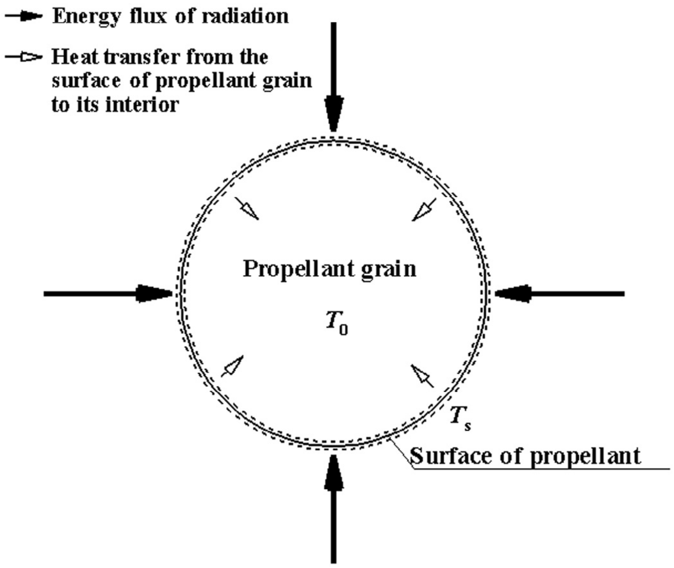

Fig. 2. Schematic diagram of propellant thermal model.