Research on ignition process of micro solid rocket motor in vacuum

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Abstract. Aiming at the ignition process of micro solid rocket motor in space, the effects of different structure on the ignition gas filling process were investigated by means of experiment and numerical simulation. By establishing numerical simulation model and the mass flow rate model of ignition chamber for black powder, pressure establishment process was researched under different parameters (the igniter quantity is 0.2g and 0.5g, outlet size of ignition chamber is $\Phi 4\text{mm}$ and $\Phi 7\text{mm}$ respectively). Meanwhile, the ignition experiment was conducted in vacuum (the ambient pressure is 16Pa) that pressure curve and vacuum plume phenomenon were obtained. The results indicate that simulation value of pressure establishing process relatively consistent with experimental one, so the mass flow rate model of ignition chamber for the black powder is evidently efficient. Therefore, the numerical method proposed in this paper can provide a theoretical basis for further research on the ignition process of micro solid rocket motor.

1. Introduction

Solid rocket motor (SRM) has broad application prospects in large scale orbit maneuver of micro-nano satellite with the superiority of simple structure, fast response, high reliability, great practical realizability in modularization and integration [1]. Working performance under different parameters is an important issue for space SRM [2]. Therefore, the experimental and simulation research of ignition and flow process is very necessary.

The mass flow rate model of ignition chamber can simplify the numerical simulation of ignition process. Mickoviá D and Jaramaz S [3] conducted theoretical and experimental research on ignition and combustion process, and obtained the influence of igniter characteristics on ignition of propellant. Junaid Godil [4] applied unsteady quasi-one-dimensional aerodynamic model for igniter mass flow rate to conduct numerical simulation of the flow field of SRM, the experimental results showed that the ignition mass flow rate model was effectively applicable to ignition process.

Calculation of internal flow field is vital for predicting the working process of SRM. Yingkun L et al. [5] and Chunqing Y et al. [6] carried out numerical simulation on the characteristics of flow field in SRM. The influence of isolation device on flow field parameters and the factors affecting ignition delay were obtained.

In experiment, Galfetti L et al. [7] applied video recording, surface temperature measurement and spectrum method to test the propellant ignition process under convection, they obtained heat transfer coefficient, ignition delay time and surface temperature finally. Moore J et al. [8] used high-speed
camera and high-response infrared radiation photodetector to conduct ignition experiment. The results have revealed the relationship between flame propagation rate and jet shape of the igniter. G Püskülcü et al. [9] conducted experimental study on ignition and combustion process under complex three-dimensional propellant grain. The influences of different grain shapes on thrust, ignition delay and combustion chamber pressurization process were obtained.

However, according to our knowledge, numerical and experimental investigations on ignition process in vacuum have not been reported yet. Therefore, to gear the needs of SRM for micro-nano satellites, this paper focuses on ignition gas filling process of black powder in vacuum, not including the propellant combustion process, and apply numerical simulation and experimental verification to research factors that affect ignition performance, such as igniter quantity, outlet size of ignition chamber and vacuum plume. As a result, it can obtain technical methods to improve ignition performance, and promote engineering application of SRM in space.

2. Experimental setup and methodology
In order to research working characteristics of SRM in vacuum and verify simulation method, this paper devised three types of vacuum ignition test motors with various structural parameters, including different outlet size of ignition chamber, expansion ratio and so on. Ignition test motors are mainly composed of forward dome, combustion chamber, nozzle, and end cover, etc. The material is modified LY12. Design opening pressure of end cover is 3MPa. Structure sketch of ignition test motors are shown in figure 1. The basic parameters are shown in table 1.

![Figure 1. Structure sketch of ignition test motor.](image)

**Table 1. Ignition test motor parameters.**

| Case   | Envelopment (mm) | Ignition chamber outlet diameter (mm) | Expansion ratio | Other                     |
|--------|------------------|--------------------------------------|-----------------|---------------------------|
| Case1  | Ф29×51.8         | Ф7                                   | 4               | /                         |
| Case2  | Ф29×51.8         | Ф4                                   | 4               | /                         |
| Case3  | Ф29×45.8         | Ф4                                   | 4               | Existing rectification section |

In order to research the influence of different structural parameters on ignition process, a vacuum ignition test system was established. The experimental set up includes vacuum containers, vacuum
pumping systems, protection boxes, pressure sensors, charge amplifier, data acquisition cards, high-speed video camera, etc. Experimental site is show in figure 2.

Figure 2. Vacuum experiment.

3. Numerical Methods

3.1. Governing equations

In this paper, a simulation model of ignition for SRM in vacuum is established. The two-dimensional axisymmetric unsteady compressible N-S governing equation is:

\[
\frac{\partial U}{\partial t} + \frac{\partial (F - F_v)}{\partial x} + \frac{\partial (G - G_v)}{\partial y} + (H_v - H_v) = S
\]

(1)

Where \( U \) is a conserved variable, \( F, G, \) and \( H \) are convective fluxes, \( F_v, G_v, \) and \( H_v \) are viscous terms. The primitive variables \( (\rho, u, v, p) \) are used as follows:

\[
U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad F = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ (e + p)u \end{bmatrix}, \quad G = \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ (e + p)v \end{bmatrix}, \quad H = \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 \\ (e + p)v \end{bmatrix}
\]

(2)

\[
F_v = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ \nu \tau_{xx} + \nu \tau_{xy} - q_x \end{bmatrix}, \quad G_v = \begin{bmatrix} 0 \\ \tau_{yx} \\ \tau_{yy} + \nu \tau_{yy} - q_y \end{bmatrix}
\]

\[
H_v = \frac{1}{y} \begin{bmatrix} 0 \\ \tau_{yy} - \frac{2}{3} \nu \frac{\partial}{\partial x} \left( \frac{\mu}{y} \right) \\ \tau_{yy} - \frac{2}{3} \mu \frac{\partial}{\partial y} \left( \frac{\mu}{y} \right) - \frac{2}{3} \nu \frac{\partial}{\partial y} \left( \frac{2}{3} \mu \frac{\nu}{y} \right) - \frac{\partial}{\partial x} \left( \frac{2}{3} \mu \frac{\nu}{y} \right) \end{bmatrix}
\]

Where relevant parameters and physical meaning can be found in reference [10].
In this paper, k-ω SST two-equation turbulence model proposed by Menter [11] is adopted to simulate the flow field. Flux difference scheme is ROE-FDS. Molecular viscosity coefficient is given by the Sutherland formula, and discretization of flow and turbulence adopts second-order upwind scheme, mass flow inlet condition for the inlet, pressure outlet condition for the outlet, no-slip wall with adiabatic condition and solid boundary for the wall in the numerical simulation process. The initial flow field pressure is 1000 Pa, which is the minimum pressure that meets the assumption of the continuous medium after the calculation, the initial temperature is 300 K, and the initial flow velocity is 0 m/s.

In order to study in detail the impact of different parameters on the internal flow field of SRM during ignition shock process, several pressure monitoring points are set in the computational domain, as shown in figure 3, where monitoring points F1-F4 are located on the surface of the propellant grain, X1-X4 are located on the central axis, J1 is located at the pressure measuring hole, and J2 is located at the nozzle convergence area.

**Figure 3.** Monitoring points in the computational domain.

### 3.2. Ignition chamber mass flow rate model

This paper adopted front ignition method in SRM, and large-particle black powder for the ignition powder [12]. Based on the zero-dimensional flow model, the mass flow rate model of the ignition chamber is established [13]. According to the law of conservation of mass and energy, the calculation equation is as follows:

$$
\begin{align*}
\frac{d(\rho V)}{dt} &= \rho_c A_b \dot{r} - \frac{PA_c}{c^*} \\
\frac{dV_c}{dt} &= A_t \dot{r} \\
\frac{d\omega}{dt} &= \dot{r}
\end{align*}
$$

Where \( V_c \) is free volume, \( \rho_c \) is density of black powder, \( A_b \) is the burning area, \( \dot{r} \) is burning rate, \( A_t \) is outlet area of ignition chamber, \( c^* \) is characteristic velocity, and \( \omega \) is burning propellant web.

In this paper, the above model is modified based on experiments. The combustion diffusion coefficient is introduced during the combustion surface propagation process. The larger the combustion diffusion coefficient, the shorter the pressure build-up time and the higher the pressure peak. The following expressions exist:

$$\alpha \eta \alpha = + - \beta \gamma = + - \delta \epsilon = + - \zeta$$

Where \( A_{bw} \) is corrected combustion area, \( A_b \) is combustion area before correction, \( \alpha \) is initial combustion particle percentage, \( \eta \) is combustion diffusion coefficient, and \( t \) is combustion time.

Substituting initial conditions into a modified black powder combustion model, the fourth-order Runge-Kutta method is adopted. The calculated mass flow rate curve is shown in figure 4. Results are input to Fluent through UDF as the inlet boundary condition.
4. Results and discussion

Based on the numerical simulation model established in this paper, the numerical calculation and analysis of the flow process were conducted under different parameters, such as igniter quantity and outlet size of ignition chamber. The vacuum ignition experiment was performed on SRM with the built-in vacuum test system.

4.1. Effect of Ignition Chamber Mass Flow Rate on Flow Field

Ignition quantity is an important factor that affects the ignition performance of SRM. Excessive mass flow rate in the ignition chamber may cause the high initial pressure peak. Therefore, a deep research of ignition quantity is necessary. This paper selected ignition quantity of 0.2g and 0.5g in Case 1 to calculation and analysis.

The pressure-time curve at end cover under the two kinds of igniter quantity for Case 1 are shown in figure 5. From the comparison of curves, the pressure increase rate of 0.5g igniter quantity is higher than the 0.2g, and end cover is opened 0.9ms earlier. From the resultant figure, we can find that as the growing quantity of black powder, the mass flow rate of ignition chamber will be higher, the pressurization rate faster, and the end cover opening time shorter. At the same time, there are fluctuations in rising phases of two curves. Because combustion chamber flow is complicated and pressure is always in unstable state. After end cover is opened, the gas flows out of nozzle, and the pressure at nozzle outlet decreases rapidly.

The pressure-time curves of all monitoring points in flow field are shown in figure 6. It is clear that under different mass flow rates of ignition chamber, the pressure changes of each monitoring point have the same trend, and the pressure difference at each monitoring point does not change much.
during the entire ignition process. The reason is that the surface of grain and ignition chamber outlet in the same level, the structure of combustion chamber is relatively simple and SRM size is small. However, the higher mass flow rate in ignition chamber is, the greater pressure shock on flow field in entire combustion chamber will be.

![Figure 6](image1.png)  ![Figure 7](image2.png)

**Figure 6.** Pressure-time curve in Case 1 of 0.2g igniter quantity.  **Figure 7.** Pressure-time curve in Case 1 of 0.5g igniter quantity.

### 4.2. Effect of Ignition Chamber Outlet Size on Flow Field

We selected Case 1 with a diameter of 7mm at the outlet of ignition chamber and Case 2 with a diameter of 4mm as the research objects. According to the mass flow rate model of ignition chamber established in Section 2.2, under the condition of the same igniter quality 0.2g, as the growing size of ignition chamber outlet, the peak pressure will be lower, and the combustion time longer.

Figure 8 shows the pressure-time curves of the Case 1 and Case 2 end cover. From the figure, it’s clear that pressure increase rate of the Case 2 end cover is higher than Case 1 and end cover opening time is shorter. The pressure-time curve at monitoring point J1 in combustion chamber is shown in figure 9. We can find that although the end cover opening time is shorter at Case 2, both Cases have similar pressure-time curves. The reason is that although the pressure peak of Case1 is smaller, the burning time is longer. Combined with figure 8-9, the ignition gas in Case 2 was ejected from nozzle in advance due to the end cover was opened earlier than Case 1, so part of the ignition gas failed to participate in the process of establishing pressure in combustion chamber. It can be explained that under the same igniter quantity, the influence of ignition chamber outlet size on monitoring point J1 is not significant.

![Figure 8](image3.png)  ![Figure 9](image4.png)

**Figure 8.** Pressure-time curve at the end cover.  **Figure 9.** Pressure-time curve at the monitoring points J1.
4.3. Experimental results
Verification experiment performed on test ignition engines, in which propellant grain was replaced by bakelite. In atmospheric pressure experiment, the influence of factors including igniter quantity and the size of ignition chamber outlet on process of establishing the pressure was researched. Furthermore, in order to reduce the randomness of black powder combustion, two groups of experiments were carried out under each condition. Due to the long cycle, high cost and the complexity of vacuum experiment, we only perform one group of Case 1 and Case 3, in which Case 3 was used to analyze the plume phenomenon.

Figure 10 shows the experimental pressure-time curve for different igniter quantity in Case 1. It can be seen that the peak pressure of combustion chamber is around 10MPa in 0.5g igniter quantity, 5.5MPa in 0.3g, 4MPa in 0.2g. All peak pressure time of the combustion chamber is around 5ms. As the igniter quantity increases, the peak pressure of combustion chamber increases, the compression rate obviously increases, and the combustion time becomes longer.

The experimental pressure-time curves of different size of ignition chamber outlets with 0.2g igniter quantity are shown in figure 11. The peak pressure of Case 2 was higher than Case 1 in each of the two tests. In the second experiment, the compression rate in rising section of Case 2 became instantaneously smaller, resulting in later peak time. The outlet of ignition chamber becomes larger, which result in smaller peak pressure of combustion chamber.

The results of atmospheric pressure experiment, vacuum experiment and simulation results in vacuum of Case 1 with 0.5g igniter quantity are shown in figure 12. The results show that the calculated values of numerical simulation are consistent with experiment. The error of peak pressure is between 5.9%-9.86%, and the error of peak time is in the range of 3.1%-6.7%. The rising trend of simulation results in vacuum are similar to the experimental values, the peak time and peak pressure are basically consistent. Therefore, the numerical simulation model established in this paper is reasonable, which can better predict gas filling process of ignition in front ignition motor. The research in this paper can provide a theoretical basis for the study of transient flow field in front ignition.
Case 3 is tested with 0.5g black powder in vacuum. Assuming that the time is zero when nozzle is about to open, the process is shown in figure 13. As the figure shows at 0.083ms, the bottom of end cover began to rupture first, and the high-temperature gas would rush out of nozzle rectifier section. At 0.167ms, the gas would rush out of nozzle from the bottom, and the end cover will completely rupture. At 0.33ms, there is still a strong gas diffusion near the nozzle rectifier section. At 0.5ms, the gas spread rapidly to the left due to the pressure difference in environment, and the mainstream formed a peak, accompanied by hot particle ejection. At 0.83ms, the initial product of gas generation has completely diffused to the left side of the protection box, at this time, the end cover ejected with rotating. Between 1.25ms and 4.33ms, the flow rate of gas was constantly changing, and it was a typical unsteady combustion, with the decline of flow rate. At 8.58ms, few remaining combustion product escape continuously from the nozzle. At 11.83ms, the ignition process is completely over.
5. Conclusion

(1) Ignition and mass flow rate of ignition chamber models for black powder were established. Based on the experimental pressure-time curve, the mass flow rate model for black powder is modified by introducing combustion diffusion coefficient. Compared the simulation results with the experiment, the method proposed in this paper is effective.

(2) The effects of design parameters including igniter quantity, outlet size of ignition chamber on the ignition performance of SRM are studied. We can draw the following conclusions. a) Increasing the igniter quantity would cause strong ignition shock on the combustion chamber, which is harmful to grain structural integrity. b) There is negative correlation between the outlet size of ignition chamber and mass flow rate. c) Ignition combustion product remaining in the experiment indicates that the larger the outlet of ignition chamber is, the larger the loss of ignition powder will be, and the ignition performance is greatly affected.

(3) The ignition performance of black powder will change in vacuum. The ignition property of black powder in vacuum is greatly affected by the environmental pressure. It is found in the experiment that 0.2g igniter quantity can’t establish the pressure to break the end cover because the low pressure leads to the decrease of combustion performance. The combustion performance of 0.5g ignition powder in vacuum is not stable. Therefore, the combustion time is shorter in vacuum than atmospheric pressure. The ejected particles do not have secondary combustion, so a large number of them remain in the environment.

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