Influence of AP on combustion and deposition of aluminum powder in combustion chamber

Jiuling Zhao

Rocket Force University of Engineering, Xi’an, PR, China

E-mail: zhaojiuling111@163.com

Abstract. In order to improve the combustion efficiency of a large solid rocket engine, it is of great significance to study the combustion behavior of aluminum powder in the combustion chamber and the mechanism and regularity of the deposition of the slag on the back wall of the latent nozzle. In this paper, the formula of propellant and the combustion chemical reaction of aluminum powder are taken into consideration. Based on the combustion model of the combustion chamber aluminum powder, the influence of the particle size and volume fraction of AP on the combustion efficiency of the propellant is studied. The conclusion has certain universality and reference significance.

1. Introduction

Large solid rocket motors mostly use aluminum composite propellant and submerged nozzle. Adding 10% to 20% aluminum powder in solid propellant formula can enhance the energy of composite solid propellant, increase the density and inhibit the unstable combustion. However, because of the condensation phenomenon in the combustion process of the propellant, there is a two phase flow energy loss between the high temperature gas and the condensed aluminum droplet, and the larger aluminum condensate is easy to burn out, thus reducing the specific impact efficiency of the propellant. The latent nozzle can effectively shorten the length of the engine, but in the working process, the condensate particles will enter the back wall of the latent section under the air flow resistance, and may deposit slag in the cavity of the back wall. The slag not only increases the negative quality of the engine, but also affects the ablation of the rear head insulation and the normal swing of the flexible nozzle. The sloshing and discharging of the slag may also cause the fluctuation of the combustion chamber pressure. Therefore, it is of great significance to study the combustion behavior and influence factors of aluminum powder in the combustion chamber of solid engine, and to understand the mechanism and regularity of the slag in the back wall of the latent nozzle, which is of great significance to improve the combustion performance of the propellant and the dependability of the large solid rocket engine [1].

The ignition and combustion process of aluminum powder in the combustion chamber, the deposition degree of the combustion products are closely related to the size distribution of the condensate particles in the engine working process, especially the condensation behavior of aluminum powder will limit the burning rate of aluminum powder and reduce the combustion efficiency of the rocket engine. The analysis of the internal factors of propellant formula (including particle size and gradation) is the main method of current research by combining theory with experimental research. However, under the restriction of the test means, the research is often aimed at the propellant material and test model engine, and the simulation method can break through the limitation. In this paper, the
propellant formula and the combustion chemical reaction of aluminum powder are added in order to get some useful conclusions [2].

2. Theoretical model of aluminum droplet polymerization on propellant surface

Basic hypothesis:

- Aluminum particles are spherical, and the influence of alumina particles on aluminum particles is ignored when aluminum particles are fired.
- The combustion of aluminum particles is a one-dimensional quasi steady combustion process.
- The combustion reaction of aluminum particles is the following simple simple gas phase reactions:
  \[ 4\text{Al} + 3\text{O}_2 = 2\text{Al}_2\text{O}_3 \]

The selection of the initial diameter of condensed particles has a great influence on the calculation results. In this paper, the theoretical model of surface aluminum droplet polymerization is adopted. This model takes into account the factors such as the particle size and gradation of AP, the particle size of aluminum powder and the pressure of the combustion.

2.1. Mathematical model

The surface combustion reaction of aluminum powder in the calculation uses a particle orbit model, that is, the Euler Lagrange model. The gas phase is treated as a continuous phase, the particle phase is treated as a discrete phase, and each particle (or particle group) is tracked in Lagrange coordinates; the gas phase combustion reaction of aluminum powder uses a two fluid model, that is, Euler Euler die. The gas phase and particle phase are regarded as continuous phase, and the particle phase is calculated based on particle dynamics [3].

2.2. Boundary condition

The exit boundary is treated with subsonic velocity and given back pressure; the wall surface is adiabatic with adhesion condition, wall surface adiabatic, and the treatment of the wall surface is more complex. Given the gas generation rate \( \dot{m} \), the wall boundary has a \( \rho V \Delta A \), and \( \Delta A \) is the wall combustion microelement area, and the \( V \) is the gas velocity perpendicular to the wall, according to the conservation of energy:

\[
T = 1 - \frac{\frac{1}{2} V^2}{\frac{1}{2} \rho} = 1 - \frac{\frac{1}{2} (V_j)^2 R^2 T^2}{\rho}
\]

As the pressure gradient of the reinforced wall is 0, the temperature can be determined, then the density and velocity are determined according to the gas equation of state, and then the velocity component is determined according to the wall inclination angle. The particles are evenly spread from the additive wall and the velocity is gas phase addition velocity. The particle sliding model and the rebound coupling model are applied on the solid side wall surface. The particle rebound model is applied to the propellant surface, and the exit particles in the combustion chamber are eliminated [4].

2.3. Computational model

The following three groups of HTPB propellants are studied.

The shape of the burning surface of 7 typical moments under the type of drug shown in figure 1 is analyzed.
2.4. Initial input
The composition of AP particles: the total mass fraction is 70% of the propellant, of which the particle mass fraction of the particle size 340um is 36% of the propellant, the particle mass fraction of the particle size 160um is 24% of the propellant and the particle size of the particle with the particle size of 7um is 10% of the propellant.

Al particle composition: 29um particle mass fraction accounted for 17% of propellant.
The ratio of surface / gas reaction: 4:6.
Combustion temperature: 3000K.
Pressure: 8MPa.
Burning rate (speed of aluminum powder adding): 10mm/s.

3. Analysis and verification of calculation results

3.1. Calculation results
The distribution of temperature, reactant and combustion product mass fraction can be obtained by simulation. According to the uniform multiphase nucleation theory, the condensation nucleation rate of the combustion product in the unit volume near a point in the combustion region is the integral of the whole combustion region, and the total number of the condensation nucleation of the combustion products is obtained. Finally, the average particle size of the combustion products of the gas phase reaction can be calculated.

Gas phase reaction part: flow velocity cloud chart is shown in figure 2. The unit of flow velocity is mm/s.
The particle content and location distribution in the surface reaction section are shown in figure 3.

![Image of particle distribution](image1)

**Figure 3.** Surface reaction particle distribution cloud map.

The curves of sediment mass flow rate versus time based on 7 typical combustion surfaces are shown in figure 4. As can be seen from figure 4, the deposition volume suddenly increases in about 30 seconds, and the deposition volume drops abruptly in more than 60 seconds. The main reason for the sudden increase is that the burning area has little change and the burning rate increases, while the main cause of the abrupt decline is the decrease of the burning surface and the decrease of the burning rate.

![Image of sediment changes](image2)

**Figure 4.** Sediment mass flow changes with time.

The curve of the combustion efficiency of aluminum powder with time is shown in figure 5.

![Image of combustion efficiency](image3)

**Figure 5.** Proportion of aluminum powder varies with time.
3.2. Result analysis
Through the analysis of the above calculation results, it can be seen that in the engine combustion chamber, with the change of the area of the flow channel, the size of the slag deposition increases gradually, and the combustion efficiency of the aluminum powder decreases gradually, and the overall combustion efficiency is greater than 94%.

Compared with the test result 48kg, the relative error is 11.7%, compared with the test result 42.39kg.

Authors should try to make economical use of the space on the page; for example:
- Avoid excessively large white space borders around your graphics;
- Try to design illustrations that make good use of the available space—avoid unnecessarily large amounts of white space within the graphic;

![Figure 6. Sediment mass flow changes with time.](image)

![Figure 7. Sediment mass flow changes with time.](image)

4. Analysis of factors affecting the size and fraction of AP
Calculation and analysis were conducted on the premise that the particle size of aluminum powder was 29um and the volume fraction of AP with a single particle size was 70%. The effect of AP particle size on cumulative deposition is shown in figure 6.

As illustrated above, with the increase of particle size of AP, the agglomeration degree of aluminum powder increases, and the combustion efficiency decreases gradually, and the cumulative deposition rate increases.

The calculation and analysis were carried out on the basis of AP with aluminum powder size of 29um and particle size of 160um. The effect of AP volume fraction on cumulative deposition is shown in figure 7.

As shown above, with the increase of the volume fraction of oxidant AP, the heat capacity increases, the combustion efficiency increases, and the total deposition decreases.

5. Conclusions
In this paper, the flow field analysis method and flow process of two combustion models, which consider aluminum powder chemical reaction and aluminum powder combustion model (gas phase reaction and surface combustion reaction), are established, and the effective analysis is carried out by this method. The results are proved to be reliable and effective. Based on the established combustion model of the combustion chamber, the effect of the particle size and volume fraction of AP on the combustion efficiency of the propellant is studied. The conclusions are of certain universality and reference for improving the combustion efficiency of the engine.
References

[1] Zhang W, Cao T, Wang N, et al. 1997 Study on agglomeration and nucleation of aluminum particles combustion and combustion products solid rocket technology 20(2) 43-46

[2] Wu X, Li X, Song G, et al. 2010 Effect of aluminum particle size on combustion performance of modified double base propellants Journal of explosives and explosives 33(3) 80-83

[3] Li S and Zhan H Q 1988 Study on aluminum combustion in propellants solid rocket technology 6(1) 69-76

[4] He G, Wang G, Cai Timin, et al. 2002 numerical simulation of internal flow field of solid rocket motor under overload condition propulsion technology 23(3) 182-185