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Effect of key parameters on the secondary combustion efficiency of boron - containing gas

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The key factors influencing the secondary combustion of solid rocket ramjet engine were summarized. The secondary combustion chamber model with front and rear inlet was established. The influence of the particle diameter and gas injection angle on the effect of cold mixing and secondary combustion was studied by numerical simulation. The results show that the smaller the particle diameter is, the more favorable the blending efficiency is and the higher the combustion efficiency is. The larger fuel injection angle is more favorable for blending, and the combustion efficiency can be improved remarkably. Increasing the air-fuel ratio can increase the gas and particle combustion efficiency. The influencing factors of working process of secondary combustion chamber are verified by numerical simulation of cold mixing and combustion process of the secondary combustion chamber. The phenomenon is explained theoretically.

Keywords: Solid Rocket Ramjet, Intake, Supplementary Combustion Chamber, Cold Flow Blending; Combustion Efficiency.

INTRODUCTION

The SIMPLE method was used by Vanka [1] to calculate the flow of the ramjet under cold flow conditions, and the vortex and backflow observed by the water flow test were reproduced [1, 2]. Chen and Tao based on the two-dimensional axisymmetric solid rocket engine model [3]. The results show that the blending and combustion process influent on the engine performance, and put forward appropriate to reduce the inlet length, reduce air-fuel ratio and reduce the Airway angles benefiting to improve blending and combustion thereby improving engine performance. Hong studied the combustion process in a two-dimensional re-combustion chamber [4]. The results show that the larger the intake angle is, the smaller the area of the back burner chamber is. At the same time, the recovery coefficient of total pressure will be lower. T.M. Liou et al. [5] showed the complexity of the flow in the secondary combustion chamber in the case of cold flow, and revealed the structure of the three-dimensional vortex in the flow field [5, 6, 7]. The concept of vortex intensity is introduced to quantitatively describe the motion of vortices, and the results reveal the movement of the vortex in the combustion chamber. Foelsche studied the effects of temperature, oxygen mole fraction, temperature and other parameters on the boron combustion process in the crystal state [8]. The results show that the burning time of boron particles will be shortened with increasing pressure.

EXPERIMENTAL

METHODS

The King model and Williams model are the most representative of the ignition model of boron particles, and the King ignition model is used to calculate the reaction flow field in the afterburner chamber as follows:

$$d_p = d_B + 2\delta \tag{1}$$

$$\frac{\mathrm{d}d_B}{\mathrm{d}t} = -\frac{2R_B M_B}{\pi d_B^2} \tag{2}$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = -\frac{\left(R_B/2 - R_E - R_H\right)M_{B_2O_3}}{\pi d_B^2 \rho_{B_2O_3}} \tag{3}$$

$$\frac{dT_P}{dt} = \frac{Q}{\left(\pi d_B^2/6\right)c_{pBL}\rho_{BL} + \pi d_B^2 \delta c_{pB_2O_3}} \quad \left(T_p > 2450K\right) \tag{4}$$

$$\frac{dT_P}{dt} = \frac{Q}{\left(\pi d_B^2/6\right)c_{pB}\rho_B + \pi d_B^2 \delta c_{pB_2O_3}} \quad \left(T_p < 2450K\right) \tag{5}$$

$$\frac{d\delta}{dt} = \frac{Q}{\left(\pi d_B^2/6\right)\rho_B \Delta H_M} \quad \left(T = 2450K\right) \tag{6}$$

$$R_B = f(d_p, T_p, p_{O_2}, \delta) \tag{7}$$

$$R_E = f(d_p, T_p, p) \tag{8}$$

$$R_E = f(d_p, T_p, p_{H_2O}) \tag{9}$$

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For the boron particle size, for the oxide layer thickness, for the melting fraction, for the particle temperature; for the boron grain consumption rate, the rate of B_2O_3 evaporation, B_2O_3 and water reaction rate, the meaning of other symbols reference [9]. The total combustion reaction of boron particles is: 2B (s) + O_2 (g) → B_2O_2 + 110kcal / mol.The burning rate is: where is the reaction rate constant.

MODELS

The physical model is shown in Figure 1. The overall mesh is shown in Figure 2. The boundary conditions were as follows: air inlet total temperature 573K, air inlet flow rate were equal, respectively, 2kg/s, four air inlet pressure 6atm. Rich gas flow 0.17kg/s. The gas inlet temperature was 1831 K and the gas generator pressure was 5 atm.There are six gas components: CO, H_2, HCl, $AlCl_3$, CO_2 and H_2O, and their mass fractions are 0.45, 0.2, 0.05, 0.15, 0.1 and 0.05 respectively. Assuming boron particles accounted for 60% of the gas, particle diameter of 2, particle temperature and velocity and gas in the same gas phase values.

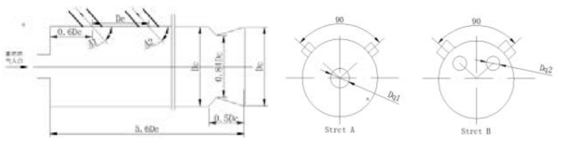


Fig. 1. Schematic diagram of the supplementary chamber

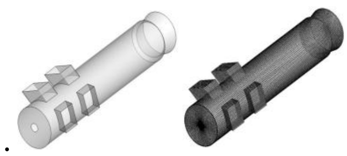


Fig. 2. Model building and meshing

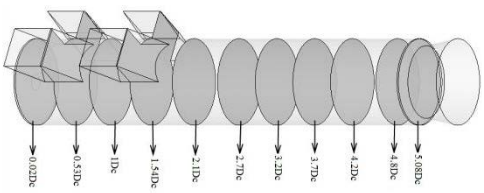


Fig. 3. Location of the cross section of the supplementary chamber

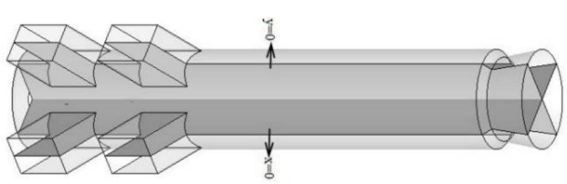


Fig. 4. Axial section of the post-combustion chamber.

When the blending degree and the dimensionless particle concentration are calculated, the cross section of the afterburner is taken as the reference, and the cross section is taken to analyze the blending degree (Figure 7 and Figure 8). The non-dimensional isobaric concentration cloud diagram, the oxygen-fuel ratio, the oxygen and particle blending degree cloud diagram are given.

RESULTS AND DISCUSSION

SIMULATION

The simulation results show that the inlet angle is 90°, the gas injection angle is 90°, the other parameters are not changed, and the particle diameter is 2 μm , 5 μm and 10 μm respectively.

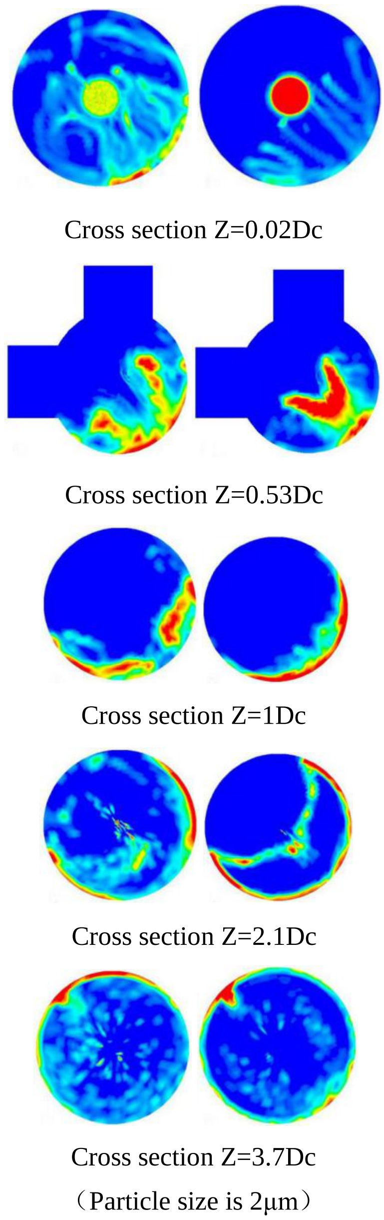
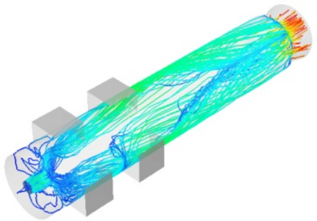
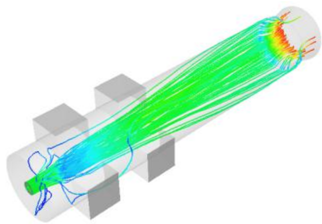


Fig. 5. Unequal particles on different cross-section concentration cloud (left particle size of 5, the right particle size of 10).

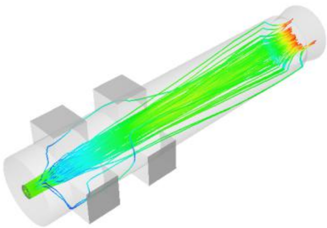
From Figure 5，With the increase of the boron particle diameter, the agglomeration phenomenon will increase, and the influence of the vortex movement on the particle agglomeration area will be weakened. Figure 6 shows that the larger the particle diameter, the worse the blending effect.From the blending curve, it can be concluded that the particle diameter is consistent with the particle trajectory, and the diameter of the small particle is better than that of the large particle diameter in the whole flow field.



(a) 2 μm



(b) 5 μm



(c) 10 μm

Fig. 6. Particle distribution in secondary combustion chamber with different particle diameters

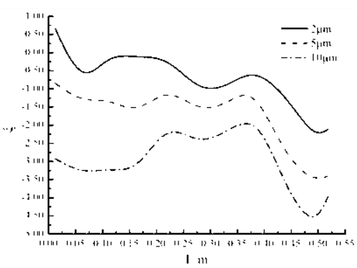


Fig. 7. Blending curves for different particle diameters

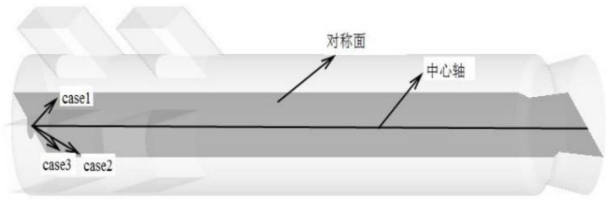
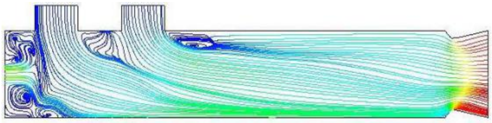


Fig. 8. Gas injection angle and the central axis angle diagram.

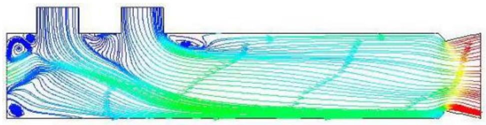
Effect of Gas Injection Angle on Gas Particle Blending

In this section, the inlet angle is 90°, the particle diameter is taken as 2 μm , and the other parameters are unchanged. The injection angle of fuel gas is 0°, 45°, -30°, -45°from the central axis of the secondary chamber, corresponding to case0, case1, case2, case3.

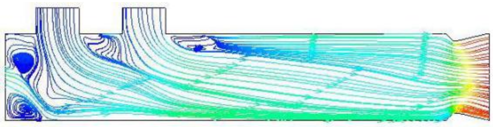
Figure 9 shows that the gas angle changes in the secondary combustion chamber head flow field impact. Figure 10 shows that the best blending effect in the head of the afterburner is case3, followed by case2, with the most severe case of particle aggregation，so that a large amount of gas enters the supplementary chamber and then flows back to the front of the supplementary chamber due to the vortex effect, thus prolonging the residence time of gas and particles in the supplementary chamber.



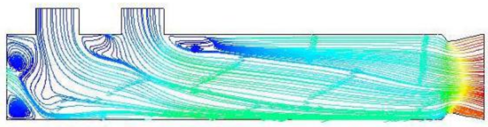
(a) case0



(b) case1



(c) case2



(d) case3

Fig. 9. Streamline of x = 0 axial section with different gas injection angles.

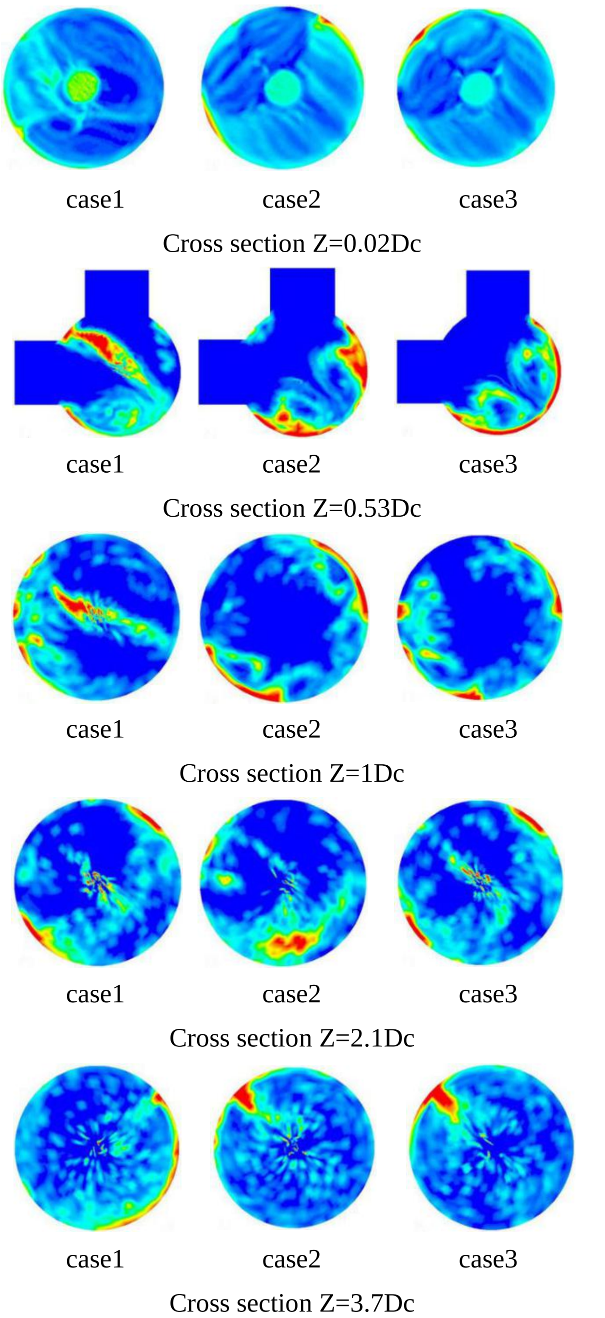


Fig.10. Dimensionless isotonic cloud plot at different cross-sections for different gas incidence angles

As can be seen from Figure 11, This shows that the gas injection angle will affect the mixing of gas particles, and the upward jet is not conducive to blending, the downward spray is conducive to blending, the 45° angle of the blending is better than 30°.

According to the blending curve of Figure 12, it can be seen that the best case of gas blending is case3, which indicates that the larger the angle of gas injection is, the more favorable the gas blending is. However, according to the study [10], when the gas injection angle exceeds a certain range, it is not conducive to reducing the primary combustion residue of the gas generator, and will affect the injection efficiency. Therefore, in the design of fuel injection angle, it should be a comprehensive study of its combustion efficiency and the impact of jet efficiency.The influence of air inlet angle on secondary combustion was investigated experimentally

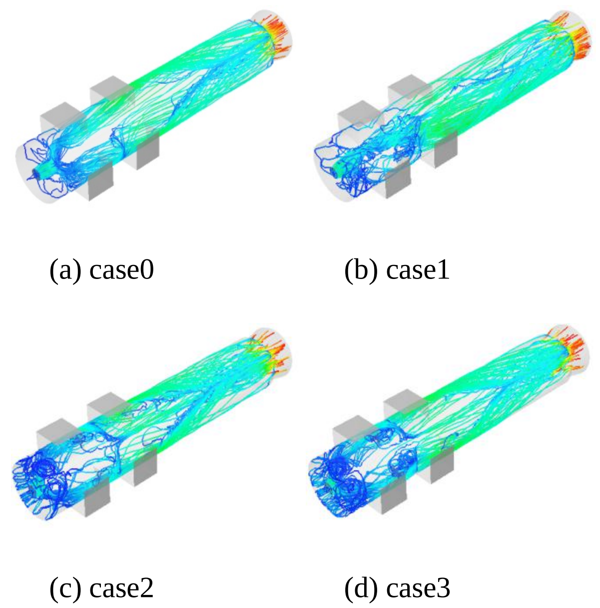


Fig. 11. Distribution of particle trajectories at different angles of incidence of gas

EXPERIMENT

The experimental design of the engine uses a modular design, can easily adjust the nozzle structure, inlet angle, head distance and length of the combustion chamber and other parameters, dual lower two-way intake, gas generator filled with boron-rich propellant short grain , Working time 10s. The simulation flight height H = 10km, the Mach number Ma = 2.8, the angle of attack α = 0°, the side slip angle β = 0°（Figure 13）.

Different air inlet angles lead to different radial velocity components of the intake air, affecting the head reflow and downstream vortex intensity and the gas and air mixing effect, thus affecting the secondary combustion efficiency. In this paper, the inlet angle of 30°and 45° is adopted, and the nozzle of the gas generator is 5 nozzles. The experimental results are shown in Table 1.

The experimental results show that the incident angle is increased, the blending effect is enhanced, and the specific impulse is increased. It is concluded that the tangential impact of the large gas inlet angle on the fuel gas is enhanced, and the area of the gas and air is relatively increased in the area of the sidewall area where the gas is forced to the relatively weak air flow, which enhances the airflow Blending, to improve the combustion efficiency. When the small angle of the inlet, gas and air interaction is weak, the two air flow into non-interfering two-tier flow, gas gathering in the supplementary chamber below, while the air is gathered in the top, the contact area of the two Small, the combustion is not sufficient, the combustion efficiency drops.

Table 1 different air intake angle combustion chamber combustion performance

Intake angle	30	45
Average air - fuel ratio	18784	17597
Burning rate	6911	7406
Theoretical characteristic velocity	91480	97670
Theoretical impulse	10438	10438
Calculate flight specific impulse	6709	8033
Specific impulse efficiency	6428	7696

CONCLUSIONS

The effects of different particle diameters and fuel gas injection angles on the mixing of particles and gas flow in the solid rocket ramjet engine were studied by mixing the boron particles and the gas in the cold flow. , And the blending of particles was quantitatively analyzed by blending, dimensionless particle cloud and oxygen-fuel ratio. The results show that:

1. the smaller the particle diameter is more conducive to blending, particle diameter is relatively small, with the flow is better, the particles with the return area of fluid movement. As the particle diameter becomes larger, the particle itself does not move with the fluid in the recirculation zone due to the high velocity of the particle itself, and the particles tend to collect towards the axis, the middle region, Mixing is not good, combustion efficiency will decline.

2. It is favorable for the blending of gas and gas when the angle of fuel gas injection is changed. The angle between the gas entrance angle and the centerline of the axial plane is more favorable for blending. When the gas injection angle is too large, it is disadvantageous for lowering the primary combustion residue of the gas generator, and the ejection efficiency is affected. Therefore, in the design of fuel-rich fuel injection point of view, it should be a comprehensive study of its combustion efficiency and the impact of jet efficiency.

3. The experimental results show that the specific impulse efficiency of 45 ° inlet is higher and the specific impinging efficiency of 30 ° inlet is lower, but the angle of incidence increases, which aggravates the deposition of combustion products in the supplementary combustion chamber.

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