Design and simulation of gas oxygen / methane vortex cooling thrust chamber

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DESIGN AND SIMULATION OF GAS OXYGEN / METHANE VORTEX COOLING THRUST CHAMBER

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Currently, the vortex cooling technology has gained wide attention as a new type of thrust chamber cooling method for liquid rocket engine in the world. Using tangential oxidant injection in the thrust chamber forms dual vortex structure thereby limits the combustion zone and avoids the sidewall temperature rise. The technology can effectively simplify the thrust chamber structure, reduce costs and increase system reliability. It is especially promising in the tiny thrust engine. Compared with hydrogen, methane has better storability characteristics and higher density specific impulse. It can be used in a variety of space missions and planetary vehicles. In this paper, a preliminary design of 300N gas oxygen / methane vortex cooling thrust chamber is performed. The influence of the fuel injection methods and the configurations of the thrust chamber on improving heat distribution of head-panel are mainly investigated. Adopting RNG k-ε turbulence model and PDF non-premixed combustion model, Fluent 6.3 commercial software was used to simulate the flow field of thrust chamber for sphere-head thrust chamber, cylindrical thrust chamber, variety of fuel injection methods (axial, impinging and tangential) and their combinations. Thrust chamber performance and the cooling wall effect of these designs were compared, and the influence of thrust chamber aspect ratio, contraction ratio and gas oxygen swirl velocity on specific performance, thermal load of the head and side wall temperature rise was analyzed in order to increase specific impulse performance and improve the heat transfer behavior of thrust chamber. The results showed that the combustion in the thrust chamber was stable. The sidewall temperature rise can be effectively reduced under a small mixing ratio (oxygen fuel ratio 2.5-4). The heat load of head-panel is significantly affected by the fuel injection method and head structure. The spherical head is helpful to avoid high head temperature. Axial and tangential fuel injection would help to improve propellant mixing and increase combustion efficiency. Combustion efficiency is increased dramatically with the swirl velocity increase of gaseous oxygen. It appears that optimum aspect ratio and contraction ratio exists when considering both specific impulse performance and head, sidewall temperature rise.

NOMENCLATURE

P_c = chamber pressure
O/F = oxidizer-to-fuel mass mixture ratio
R_f = fuel distribution radius
R_c = chamber radius
R_t = nozzle throat radius
L = chamber length
R_n = nozzle inlet radius
ΔP = pressure drop
Γ = diffusion coefficient
S_Φ = user-defined source item
k = kinetic energy
ε = turbulence eddy
α = fuel injection angle
β = oxygen injection angle
ρ = density
U = velocity vector
x = coordinate system
η_{sp} = specific efficiency
T_{av} = average temperature

I. INTRODUCTION

As a new type research of liquid rocket engine, vortex injection techniques [1] have gained widespread attention at home and abroad. Unlike traditional thrust chamber, injection of vortex cooling thrust chamber is usually arranged at both ends of the thrust chamber, as shown in figure 1. Gas oxygen is tangentially injected at the end of the thrust chamber, and forms a vortex flow field of inner and outer vortex layer, which are coaxial and reverse. Due to this special structure of flow field, the propellant flow mixing and combustion is limited in the core inner vortex, while outer vortex prevents the contact of high temperature gas with the wall surface, and then reduce the surface heat load caused by chemical combustion and heat convection. At the same time, high-speed rotating vortex effectively improved the side wall temperature rise.

The technology was first proposed by the Orbital Technology Corporation. It focused on test research and technology validation[1-3] of a hydrogen / oxygen vortex cooling thrust chamber, and obtained rich test data. The main factors affecting the thrust chamber specific

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impulse performance and the key structure of heat load were analysed and summarized.

Research showed that, the vortex injection techniques could eliminate cooling structure, so as to effectively simplify thrust chamber structure design, reduce development cost, increase chamber life and improve safety and reliability. The characteristics of the side wall of low temperature, has great potential applications[4-5] in the upper stage small thrust engine. And the engine has the characteristics of fast ignition, steady-state operation under low temperature, high performance etc.

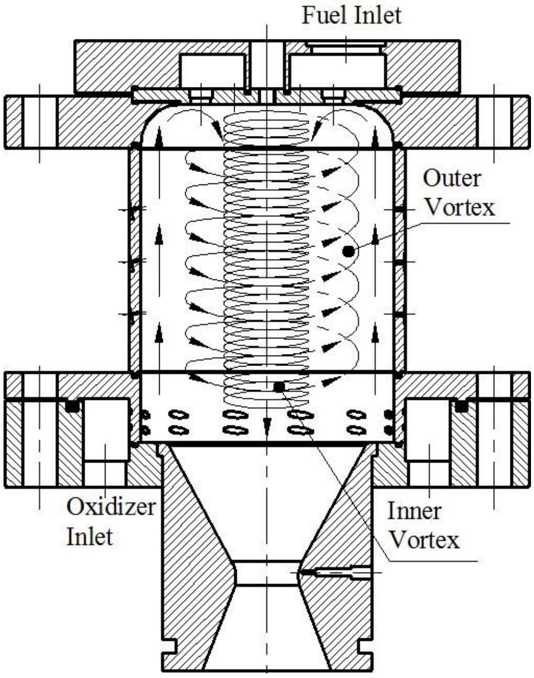
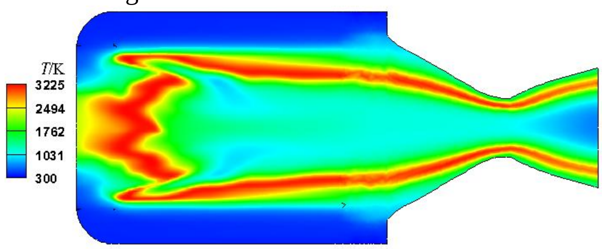


Fig.1 Vortex cooling thrust chamber structure and flow schematic

In China, Jiawen Li and others of Beijing University of Aeronautics and Astronautics focused on different thrust level test and combustion visualization. Their results confirmed research of Martin[1, 3, 4] et al. Experimental results[6] showed that, good cooling effect of thrust chamber side wall was obtained, but ablation existed near the head and fuel injection panel, and specific impulse efficiency needs to be improved. The conclusion was also proved in the simulation of the flow field characteristics of the thrust chamber, as shown in figure 2.



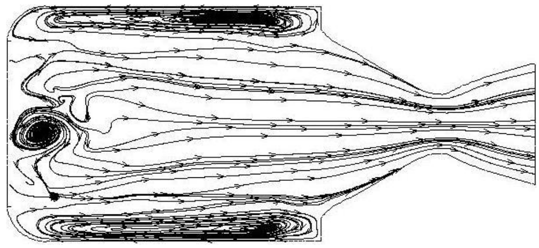


Fig.2 Simulation results of the characteristics of thrust chamber flow field

The simulation shows the existence of a low velocity recirculation zone in the thrust chamber head, where the high temperature gas cannot be took away, resulting in high temperature head panel. At the same time, ineffective mixing of part of the axially injected fuel leads to loss of specific impulse thrust.

Taking into account many excellent features[7] of methane when adopted in upper stage small thrust engine applications, this paper adopts gas oxygen / methane propellant combination. After standard design of the thrust chamber, thrust chamber performance simulation calculation of the fuel injection methods, special thrust chamber configuration, thrust chamber structure parameters and gas oxygen flow parameters were conducted. Changing rule of vortex cooling thrust chamber performance with parameters, and influence of thrust chamber parameters on the thermal load of key structure (head, side wall) are studied to provide basis for the design of engine.

II. METHOD OF APPROACH

II.I Work Conditions

The combustion chamber pressure was Pc=1MPa, mixing ratio was O/F=2.757, and ground thrust was 300N. Referring to the previous design experience[8] of test structure components of hydrogen/oxygen vortex cooling thrust chamber, two kinds of thrust chamber of plane and spherical head were designed, as shown in figure 3.

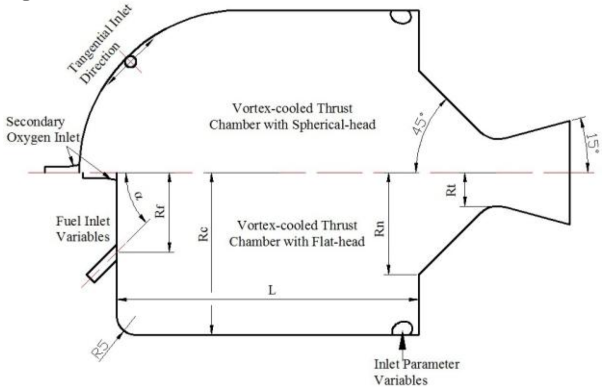


Fig. 3 Schematic profile two kinds of thrust chamber design

To ensure same thrust chamber volumes, the thrust chamber of spherical head is slightly longer than the cylindrical thrust chamber. The nozzle throat size and shape of the two chambers keep invariant in order to offset the estimation error of thrust chamber performance caused by nozzle efficiency changes. 4 groups of numerical calculation were carried out respectively, including research on the influence of fuel injection effect (A), special head (B), structure parameters (C) and oxygen gas flow parameters (D) on thrust chamber performance and heat load of key structures. The detailed calculation conditions are shown in table 1-4.

Table 1 Group A calculation conditions

No.	R_f/R_c(%)	α(deg)	sec-oxy
#1/2	30	0/45	N
#3/4	40		
#5/6	50	0/15	N
#7/8		30	N/Y
#9/10		45	
#11/12		60	
#13		75	N
#14/15	60	0/45	N
#16/17	70		

Table 2 Group B calculation conditions

No.	inlet direction	rotary direction	sec-oxy
#18/19	up	——	N/Y
#20		co-axis	N
#21		op-axis	N
#22/23	down	——	N/Y

Table 3 Group C calculation conditions

No.	R_c/R_t	$L/2*R_c$	R_n/R_c(%)
#24	4	0.8	90
#25	4	1.6	85
#26	4	2.4	80
#27	4.5	0.8	85
#28	4.5	1.6	80
#29	4.5	2.4	90
#30	5	0.8	80
#31	5	1.6	90
#32	5	2.4	85
*33	the possible test of the optimal structure		

Table 4 Group D calculation conditions

No.	O/F	$\Delta P/P_c$(%)	β(deg)
#34	2.5	5	0
#35	2.5	10	5
#36	2.5	15	10
#37	2.5	20	15
#38	3	5	10
#39	3	10	15
#40	3	15	0
#41	3	20	5
#42	3.5	5	15
#43	3.5	10	10
#44	3.5	15	5
#45	3.5	20	0
#46	4	5	5
#47	4	10	0
#48	4	15	15
#49	4	20	10
*50	the possible test of the optimal oxygen flow parameters		

The A\C\D three groups were calculated using the cylindrical thrust chamber, while group B was calculated using the spherical head thrust chamber. A\B groups focus on the impact trends of fuel injection methods and thrust chamber head configuration of vortex cooling thrust chamber on specific impulse performance and head temperature rise, as well as the comprehensive effects of the central secondary oxygen injector. C\D groups focus on the investigation of structural parameters and gas oxygen flow parameters' influence on the thrust chamber. To eliminate the effect of head structure and fuel injection methods, the axial flow injector is adopted, and R_f/R_c=50%.

II.II Numerical Simulation

II.II.I Governing Equations

The governing equations were discretized using a finite volume method. And the pressure-based segregated algorithm was employed to solve the discretized equations.

$$\frac{\partial}{\partial t}(\rho\phi)+div(\rho U\phi)=div\left(\Gamma_\phi grad\phi\right)+S_\phi \qquad [1]$$

where ϕ is a general variable which represents the axial velocity, radial velocity, tangential velocity, temperature or mass fraction.

The RNG k-ε turbulence model was used in this paper and the transport equations for the kinetic energy and turbulence eddy were given as follows.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right) \qquad [2]$$
$$+G_k+G_b-\rho\varepsilon-Y_M$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right) \qquad [3]$$
$$+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon$$

Reaction mechanisms are simulated using the non-premixed combustion model. It has advantage when simulating the diffusion flames of turbulence state of fast chemical reaction compared with finite rate method. The transport equation of the mixture fraction f is:

$$\frac{\partial}{\partial t}\left(\rho\overline{f'^2}\right)+\nabla\cdot\left(\rho U\overline{f'^2}\right)=\nabla\cdot\left(\frac{\mu_t}{\sigma_t}\nabla\overline{f'^2}\right) \qquad [4]$$
$$+C_g\mu_t\left(\nabla\overline{f}\right)^2-C_d\rho\frac{\varepsilon}{k}\overline{f'^2}+S_{user}$$

$f' = f - \overline{f}$, where $\overline{f}$ denotes the mean mixture fraction. 15 combustion components were added: CH_4, O_2, CH_2O, CO, CO_2, H, H_2, H_2O, H_2O_2, HCO, $HCOOH$, HO_2, $HOCO$, O, and OH.

II.II.II Boundary Conditions

To save compute resources, 1/6 calculation model was selected, and periodic boundary condition was adopted for the two sections. The grid size ranges from 40 million to 200 million. The calculation model and mesh are shown in figure 4.

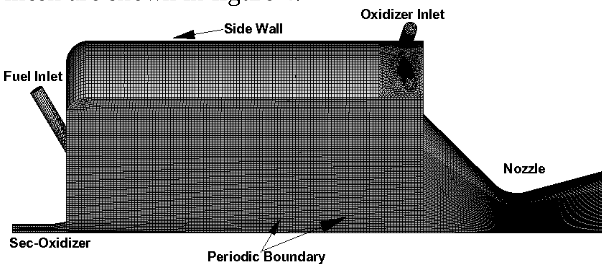


Fig. 4 Vortex cooling thrust chamber schematic of calculation model

The mass flow entrance and moderate turbulence intensity were adopted. The methane flow rate is 5.92g/s, and the gas oxygen flow rate was adjusted according to the mixing ratio. The secondary oxygen injector flow rate was fixed at 1.43g/s. Pressure outlet was adopted, and ambient pressure was 1atm. Adiabatic wall of no slip was chosen, and effect of radiation was not considered. The injector entrance pressure was 1MPa, and the initial temperature was 300K.

III. RESULTS AND DISCUSSIONS

Since it is difficult to estimate the combustion efficiency of vortex cooling thrust chamber[8], the specific impulse efficiency was adopted to evaluate the performance of the thrust chamber, and average temperature rise of head and side wall were used for the assessment of heat load of key structures.

III.I Fuel Injection Effect

The impact trends of distribution radius of the fuel injectors on the thrust chamber specific impulse performance and the temperature rise of the thrust chamber head are shown in figure 5 and 6.

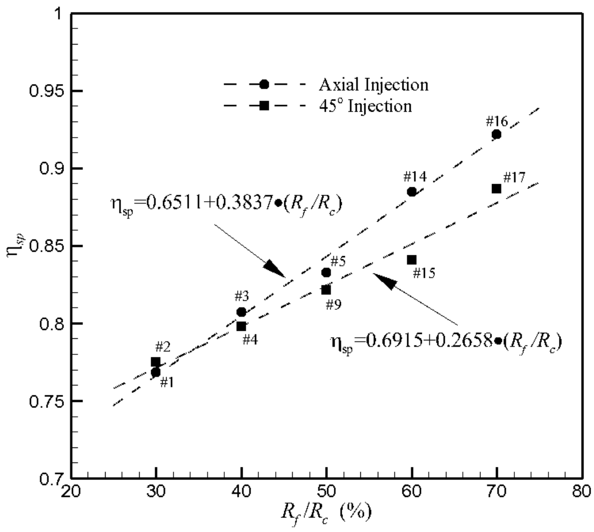


Fig. 5 Impact of injector distribution radius on specific impulse performance

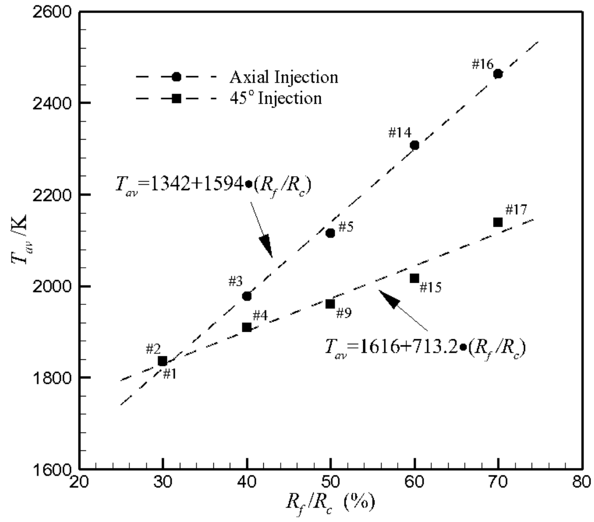


Fig. 6 Impact of injector distribution radius on the total temperature of the head

Figure 5 shows that, using the two kinds of typical injection scheme, namely axial and 45 ° impinging types, thrust chamber specific impulse efficiency increased significantly when the fuel injector distribution radius increased. When employing same distribution radius, the axial injection is superior to the impinging type, and the maximum efficiency difference of them is about 5%. With the injector distribution radius increases, the specific impulse efficiency of the axial type increases from 77% to 92%, while that of the impinging type increases from 77.5% to 88.2%.

As figure 6 shows, the influence of the fuel injector distribution radius on the head temperature rise is similar to that on the specific impulse efficiency. When using the same distribution radius, the temperature rise of impinging type is less than the axial type, and the maximum temperature difference is about 400K. High specific impulse performance brings the high temperature rise of the head, which is consistent with the conclusion of Martin's test[1, 2].

Analysis shows that there are more methane at the head centre of thrust chamber of impinging type than axial type. Thus the injection panel can be covered fully in order to improve the head temperature rise. When employing impinging type injectors, it is faster and earlier for methane to concentrate on the centre of the head, which is not conducive to the mixing with the outer gas oxygen vortex. So the efficiency of impinging type is slightly less than that of axial type. In addition, significant effect of the fuel injectors is mainly reflected near the head of the thrust chamber. With further development of the flow field, combustion of thrust chamber is mainly influenced by gas oxygen vortex. Therefore the two injection schemes have similar changes of specific impulse performance.

The influences of fuel injection angle and central secondary oxygen injector on specific impulse performance of thrust chamber and temperature trend of the head are shown in figure 7 and 8.

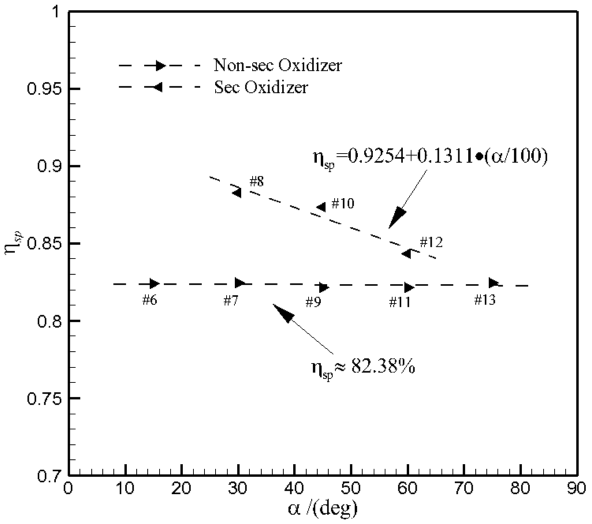


Fig.7 Influence of injection angle and the secondary oxygen injector on specific impulse performance

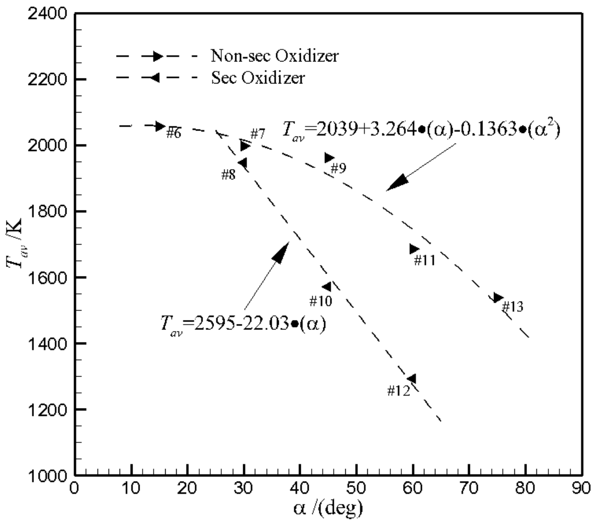


Fig. 8 Influence of injection angle and the secondary oxygen injector on the head total temperature

As shown in figure 7, the injection angle change of methane has no obvious influence on the thrust chamber performance, while the change of specific impulse is less than 1%. The specific impulse efficiency of the 5 groups is about 82.38%. Arrangement of the central secondary oxygen injector can significantly improve the specific impulse efficiency by 3%-7%. This is because the secondary oxygen injector can improve oxidizer-to-fuel mixing ratio near the centre of the flow field to increase combustion efficiency. But increasing injection angle decreases the trend of specific impulse growth. This once again proves that the effect of injection angle is offset with further development of the flow field.

From figure 8 we can know that the head total temperature decreased significantly with the increase of injection angle. The change of injection angle is 15 °-75 °, while the total temperature change is 2050K-1500K. This shows that greater injector angle will help reduce the head temperature rise. The arrangement of the central secondary oxygen injector can enhance the head cooling effect of injector angle. The minimum head total temperature in the calculation appeared in #12, about 1293K.

Analysis shows that, the specific impulse performance when using the fuel injection with injection angle is lower than using axial injection. However, the specific impulse is insensitive to injection angle, and wide injection angle is conducive to improve the head total temperature rise. According to preliminary estimates of each fitting curve of figure 5-8, the injection scheme when adopting the secondary oxygen injector, the fuel injector distribution radius is 70%, and injection angle is 60 ° can balance the specific impulse performance and head temperature rise. The result for the specific impulse efficiency is about 90.5%, and the head temperature is about 1480K.

III.II Hemisphere Head Analysis

Adopting tangential injectors can effectively make methane cover thrust chamber head, thereby improving the head temperature distribution. The injection method of direct cooling head by using propellant is in accordance with the original intention of vortex cooling thrust chamber concept. The thrust chamber specific impulse performance and head temperature rise of the combination of spherical head and tangential injectors are shown in figure 9.

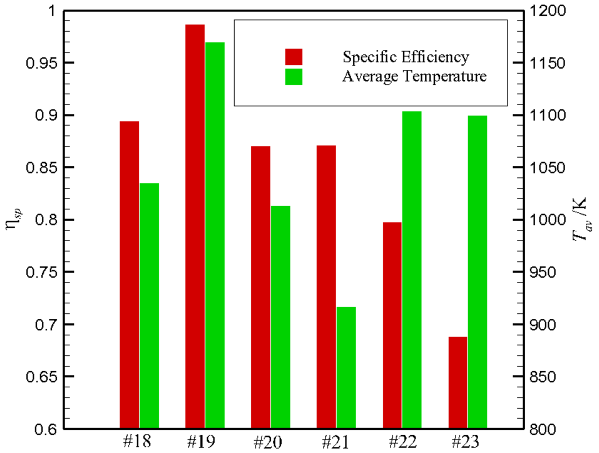


Fig. 9 Specific impulse efficiency, average total temperature contrast of group B

As illustrated in figure 9, the injection schemes (#18~#21) that injecting toward head are superior to the injection schemes (#22, #23) that injecting toward chamber body. The direction of rotation of methane injection influences little on specific impulse. The specific impulse efficiency of #20 and #21 is slightly lower than the non-rotating #18. The scheme #19 which is non-rotating, injects toward head and has the central secondary oxygen injector has the highest specific impulse efficiency 99.1%. The scheme #23 which is non-rotating, injects toward chamber body and has the central secondary oxygen injector has the lowest specific impulse efficiency which is about 68.7%.

Comparison shows that the influence trends of the combination of the secondary oxygen injector and the two tangential injection methods are opposite and have similar amplitude which is about 10%. Analysis shows that, #22 and #23 methane injection location which is away from the centre of the head makes the thrust chamber mixing space shorter, and the secondary oxygen injector cannot contact with fuel well, so the specific impulse efficiency would decline.

From the comparison of the head total temperature of every group, temperature rise of six groups were close to each other. The scheme #19 has the highest specific impulse performance and the maximum temperature 1170K. The scheme #21 which injects toward head and opposite with the direction of gas oxygen rotation has the lowest temperature 920K. The temperature field and streamline near the head of thrust chamber are shown in figure 10.

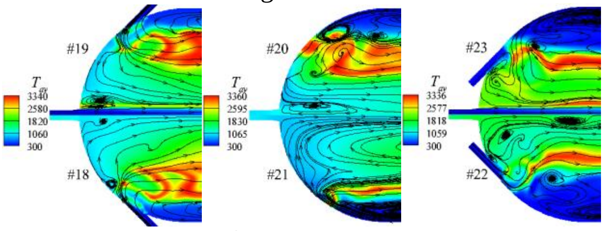


Fig. 10 Temperature field and streamline charts near the head of thrust chamber

Combining with the figure 10's analysis, the method injecting toward head can make methane better cover the entire head and significantly reduce the head temperature rise. The injection scheme that injects toward chamber body makes the mixing of propellants, combustion and heat transfer away from head, thereby reducing the total temperature rise, but bringing significant decrease of specific impulse.

In addition, the head temperature rises of the thrust chamber of group B are all lower than that of group A. This shows that the spherical head is better than the plane head when improving the head temperature distribution. This conclusion is very close to the results of spherical head thrust chamber in reference [4]. The calculation also indicates that, the spherical head is more sensitive to the fuel injection methods. Selecting appropriate combination of fuel injection method can greatly improve the specific impulse performance of thrust chamber. Preliminary estimates show that using #21 and arrange the secondary oxygen injector can balance the specific impulse performance and temperature distribution of the head.

III.III Structure Parameters Analysis

Taking into account that change of the thrust chamber length-diameter ratio and contraction ratio will bring great volume change of combustion chamber, if O/F=2.757 is still used in larger combustion chamber volume it may adversely affect the cooling effect of the side wall. Group C is calculated using O/F=4 and the thrust is about 376N. Using the specific impulse efficiency as the orthogonal test response, sensitivity of three structure parameters on specific impulse performance was compared through the mean response amount and range. The influence of structure parameters on specific impulse performance is shown in figure 11. Figure 12 evaluates the relative sensitivity of the three structure parameters on the specific impulse performance of thrust chamber.

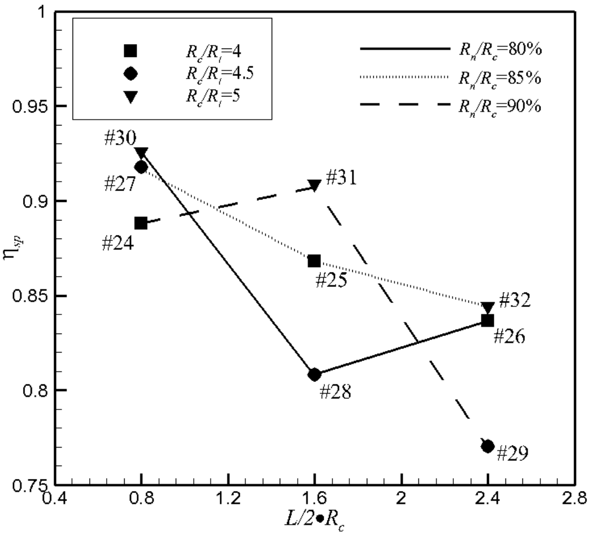


Fig. 11 Influence of structure parameters on specific impulse performance

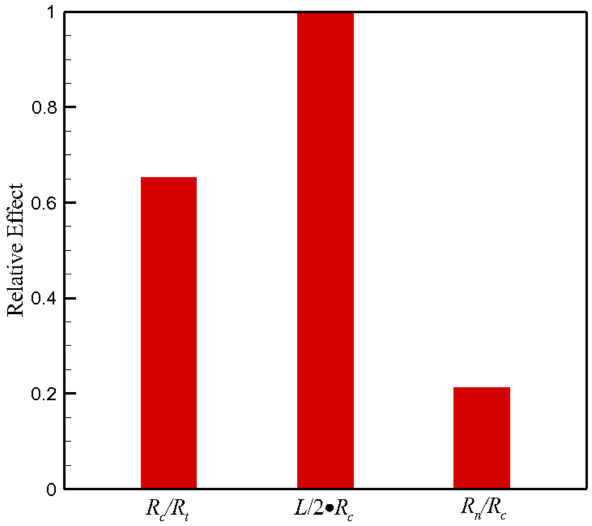


Fig. 12 Sensitivity analysis of structural parameters on specific impulse performance

According to figure 11 and 12, the most significant factor affecting the specific impulse performance of thrust chamber is length-diameter ratio, followed by contraction ratio. When the contraction ratio keeps constant, the specific impulse efficiency decreases significantly with the increase of length-diameter. When the length-diameter keeps constant, the best specific impulse efficiency is obtained at area ratio 5. The space reserved for outer vortex, which is the same as the ratio of the nozzle entry radius and thrust chamber radius, has the lowest influence on the specific impulse efficiency. This is basically the same as the test results of the hydrogen / oxygen vortex cooling thrust chamber of the Martin, et al[2].

Analysis shows that, the vortex cooling thrust chamber drives the fuel mixing and reaction combustion by high-speed swirling gas oxygen. Therefore, improving and maintaining the speed of vortex in the reaction zone is the key to improve the mixing effect and specific impulse efficiency. In general, small length-diameter ratio and big contraction ratio are conducive to reduce gas oxygen vortex rise distance, thereby reducing the vortex speed consumption, and improving the specific impulse efficiency.

III.IV Oxidizer Injection Effect

The optimal thrust chamber structure #30 in group C is used for the standard thrust chamber to study the influence of oxygen flow parameters. The specific impulse efficiency is still adopted as the main response in group D, while the average temperature rise of the side wall is adopted as the auxiliary reference quantity. Theoretical thrusts corresponding to O/F=2.5, 3, 3.5, 4 are 280N, 318N, 349N, 376N. Influence of oxygen flow parameters on specific impulse efficiency and side wall temperature rise are shown in figure 13 and 14. The relative sensitivity of flow parameters on specific impulse performance and the side wall temperature rise are evaluated in figure 15.

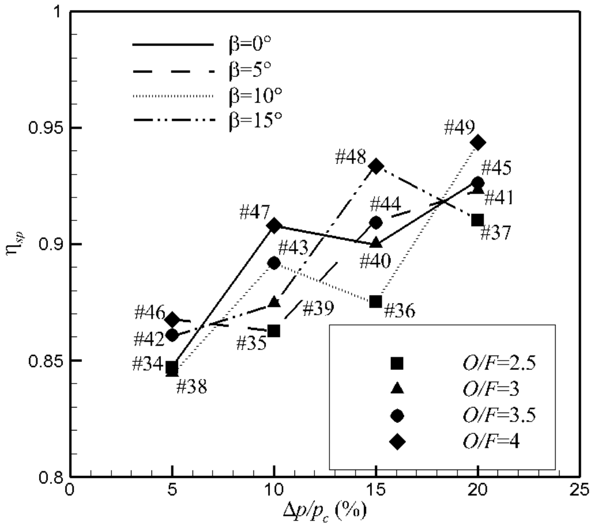


Fig. 13 Influence of gas oxygen flow parameters on specific impulse performance

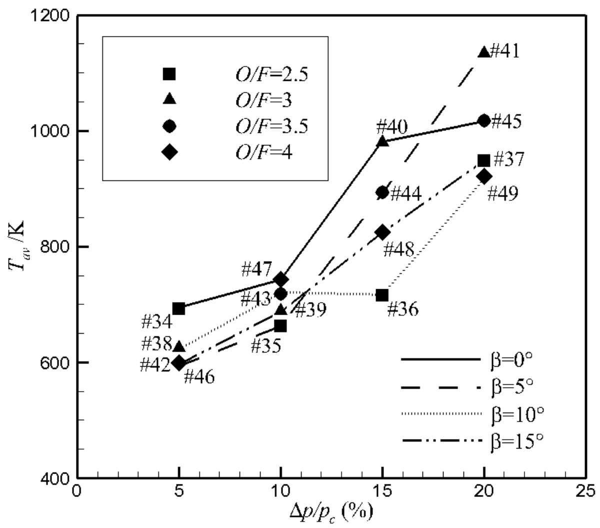


Fig. 14 Influence of gas oxygen flow parameters on side wall temperature rise

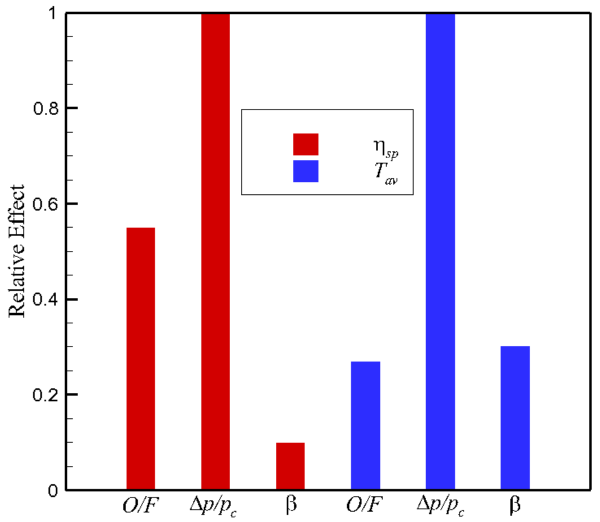


Fig. 15 Sensitivity analysis of flow parameters on specific impulse performance and the side wall temperature rise

According to figure 13 and 15, the sequence of parameters which influence the specific impulse efficiency are: oxygen pressure, mixture ratio and inclined angle of oxygen injector. The specific impulse efficiency increases significantly with the increase of injection pressure drop and/or mixing ratio. The highest specific impulse efficiency is 94.3% of #49. It has the mixing ratio of 4, and oxygen pressure of 20%. Increase of injection pressure drop and mixing ratio is helpful to increase entrance vortex velocity, thus the specific impulse efficiency can be improved. But in practice mixing ratio and injection pressure drop cannot be increased unlimitedly (this will bring great difficulties for supply system). So there should be a reasonable choice of injection pressure drop and mixing ratio. In addition, gas oxygen / methane mixture ratio deviates from traditional engines, which also imply the existence of local mixing ratio in vortex cooling thrust chamber.

The injector angle has little effect on the specific impulse efficiency. This may be because the increase of inclined angle could improve the axial velocity component which makes the vortex easier to get to the thrust chamber head, but reduces the entrance swirl velocity component. The effects of them are offset.

As is shown in figure 14 and 15, the parameter which influences the side wall temperature most is the oxygen pressure drop, followed by mixing ratio and inclined angle. The latter two factors have equivalent effect on side wall temperature. When the mixing ratio or the inclined angle keeps constant, increasing the injection pressure drop will lead to rising of side wall temperature, namely, smaller injection pressure drop is conducive to reducing side wall temperature. This is because under calculation conditions, small pressure drop is equivalent to large entrance area, namely more gas oxygen will flow past side wall per unit time, resulting in improving the cooling effect of side wall. #38, #42 and #46 have the minimum wall temperature which is about 600K. This shows that when the injection pressure drop keeps as small as 5%, the mixing ratio has little effect on the side wall temperature rise. When employing high injection pressure drop (15%-20%), increase of the inclined angle can obtain low temperature rise of the side wall.

It is worth noting that injector pressure drop is the most significant factor which influences specific impulse efficiency and side wall temperature, but their trends are the same, i.e. high specific impulse also brings high temperature rise. Taking into account the good effect of wall cooling in the previous test[9], high pressure drop should be adopted to increase the specific impulse efficiency. And large angle $\beta \geq 10$ ° should be used in order to reduce the side wall temperature.

IV. SUMMARY AND CONCLUSIONS

Although many simple numerical models were adopted, actual methane reaction mechanism of combustion was not calculated, and factors such as the wall surface radiation effect and interaction of turbulence and combustion were also not considered, the flow characteristics of vortex cooling thrust chamber was basically revealed. Trends and rules obtained in the paper can be understood and confirmed by many tests[3, 4, 6] and simulation results[10-12]. The paper has positive significance for further research and test design in the future.

Influence of fuel injection method, thrust chamber head configuration, thrust chamber structure parameters and gas oxygen flow parameters on engine performance and heat load of key faces are summarized and analyzed by four groups of simulation calculation. Main conclusions are:

1 With the increase of fuel injector distribution radius, the specific impulse efficiency and thrust chamber head temperature increased significantly. Larger injection angle is conducive to cooling thrust chamber head, but the specific impulse efficiency of the engine is lower than that of engine with axial injection.

2 The central secondary oxygen injector improves the combustion at the centre of the thrust chamber, thereby increasing the specific impulse efficiency.

3 The spherical head can reduce the heat transfer towards the head during the combustion process. The way fuel covers the head or make injection locations away from the head can reduce the head temperature. The highest specific impulse efficiency is up to 99%.

4 Small length-diameter ratio (0.8) and large contraction ratio (5) are helpful to improve the specific impulse efficiency. This implies the control method of the vortex cooling thrust chamber mixing and combustion process. It is better to keep vortex velocity rather than increase axial distance.

5 The oxygen pressure drop has similar significant influence on specific impulse efficiency and side wall temperature rise. The oxygen injection combination of larger injection pressure drop (20%) and larger inclined angle (15 °) is beneficial for both specific impulse efficiency and side wall temperature.

It is necessary to carry out related hot flow test to verify the simulation results, and conduct detailed simulation of secondary oxygen injectors' arrangement, distribution, pressure drop and flow rate to make its effect on specific impulse efficiency clear.

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