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Numerical Study on Configuration of Scramjet Combustor

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Abstract. The numerical simulation has been carried out to further investigate the cold flow characteristics for mixing efficiency and flame stability of the composite structure of pylon and cavity in the supersonic combustor and optimize the supersonic combustor flow field. It is found that the pylon can greatly improve the penetration depth of the jet and enhance the blending, and it will not bring the greater total pressure loss. Cavity can promote the diffusion of ethylene and improve the penetration depth of fuel, but also cause greater total pressure loss. The combination of the pylon and cavity can make good use of the advantage of the each single device and the geometry dimension and the combination mode of the pylon and cavity can be further analyzed from to improve the performance of the scramjet engine in next step.

1. Introduction

The supersonic combustor is one of the most important part of the scramjet engine[1-4]. In the supersonic combustor, a series of physicochemical changes such as mixing and combustion should be completed in limited space, very short time and complex flow state, and the performance loss of scramjet engine should also be reduced as much as possible. This is a very challenging task, and it is also the core problem to be solved in the design of scramjet engine. To improve ignition and flame stability, Russian Federal Central Space Agency took the lead in the successfully application of cavity flame stabilizer in scramjet combustor. Since then, the device has attracted the attention of researchers [5].Cavity has excellent flame-stabilizing ability, but because of its direct injection on the combustor wall, the fuel and its combustion products mostly stay in the cavity and near the combustion chamber wall [6-8]. This is not only unfavorable to the mixing of fuel and air, but can not make full use of the combustor space, but also increases the heat resistance requirements of the combustor material.

The reasonable structure design before the cavity can enhance the flame stability while enhancing the fuel flow mixing and improving the comprehensive performance of the combustor[9-10].To this end, domestic and foreign scholars proposed hybrid enhancement devices such as slopes, strut, and tabs[11-12]. Recently, pylon, a more promising structure, has been proposed on the basis of the strut[13-17].The test and simulation results show that all the hybrid augmentation devices have their own advantages in enhancing mixing, improving penetration depth, reducing total pressure loss and stabilizing flame and so on, but also have their own deficiencies. A more ideal combustion chamber fuel injection scheme may be obtained by a reasonable combination of different devices.

In this paper, the numerical simulation method has been carried out to analyze the influence of the pylon and cavity structure on the flow field of the combustor and its mechanism. The qualitative and quantitative research is conducted from the aspects of fuel distribution, mixing efficiency, and total pressure loss to analyze the advantage of the combination of pylon and cavity, which will provide an important reference for the design improvement of the scramjet engine [18].

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2.Calculation setting and grid partition

To deeply study the influence of the combination of pylon and cavity on the flow field of the scramjet combustor, three cases are given in reference of the literature [13] and the literature [15]. See Table 1 for details. The "√" indicates that the hybrid enhancement device is applied in the case.Figure.1 shows the basic conFigureuration of the combustor where cavity and pylon are combined and the combined distance is L_C=6d, where d=1.4mm. A rectangular cross section free channel conFigureuration is adopted in the supersonic combustor to eliminate the interference of other factors. It can be seen from the Figure that the height of the combustion chamber is 25.4mm, the width is 24mm, the total length is 180mm, the pylon heigh is 5.6mm, and it is 35mm from the inlet of the combustor. The depth of cavity is D=14mm, the length is L=42mm, and the back edge angle is 45 degrees. The injector uses the square with side length a=1.24mm to facilitate the modeling and calculation (the area is equivalent to a circular hole with a diameter of d = 1.4), and the distance between the pylon and injector is 2d.

Table 1. Calculation setting

case	case1	case2	case3
cavity	√		√
pylon		√	√

The Mach number in the case is Ma=2, total pressure P_t =850KPa, static pressure p=108KPa, temperature T_t =300K, the mass fraction of the composition of the flow is α_{O_2} =23.2%, α_{N_2} =76.8%. The total pressure of ethylene injection is P_t =20000KPa, static pressure p=1400KPa, temperature T_t =1200K. The Fluent software was used to simulate the cases, SST $\kappa-\omega$ turbulence model was adopted in the numerical simulation, and the non-slip walls were used. The ICEM is used to structurally mesh all the computational domains, and mesh refinement is performed near the pylon, injector and cavity wall. The first grid node is 1×10-6m from the wall, and the number of grids in each model is about 3 million. Figure .2 shows the grid of the case3 scramjet combustor.

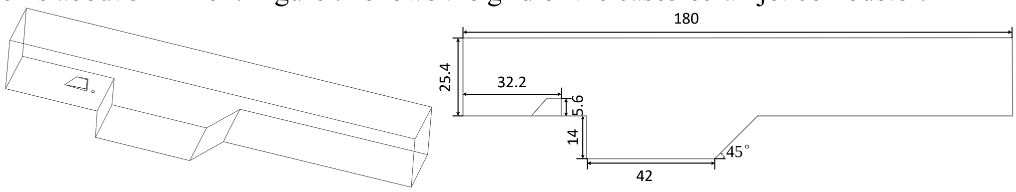

Figure 1. Schematic diagram of combustor conFigureuration (Unit: mm)

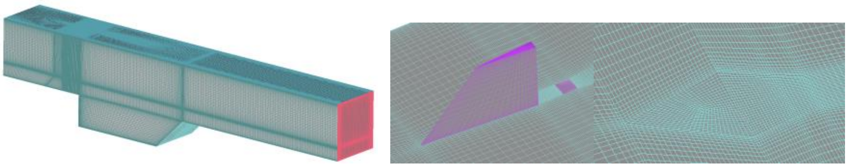

Figure 2. Schematic diagram of the combustor grid

3.Result analysis

3.1.Effect of pylon on performance of scramjet combustor

Figure.3 shows the pressure contours of the symmetrical section of the combustor. The former is the case1 pressure contour, which produces strong shock waves near the injector, while the latter is case3 pressure contours, and the shock wave is mainly generated on the upper edge of the pylon. With the flow movement, both shock waves are refracted through the wall and form shock waves strings in the combustor. Because the shock wave can cause the decrease of the flow velocity, it will lead to the loss of the total pressure. It can be found that the structure of pylon changes the position of the shock wave, and the shock intensity of case3 is slightly lower than that of the former. The shock waves distribution at the rear end of the combustor also hardly affected, and the shock intensity of case3 was slightly larger than that of case1. It is worth noting that case 3 can produce a larger low pressure zone behind the pylon, which will bring more obvious advantages to improving jet injection height and accelerating the mixing between fuel and incoming flow.

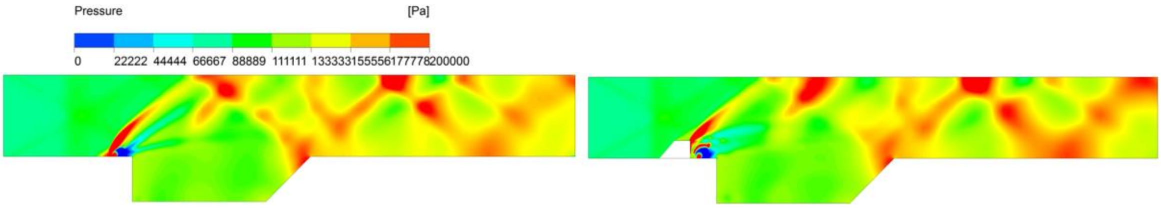

Figure 3. Pressure contours

Figure.4 is a plot of the equivalence ratio of the ethylene composition $0.4 \le \Phi \le 5.5$ and the $\Phi = 0.2$ isoline on the section X = 25d, 30d, 35d, 40d, 45d, 50d, 60d, and 70d for cases 1 and 3, respectively. The size of the contours represents the area of the combustible mixture. Outside the contour is the equivalence ratio line, and the equivalence ratio line contains the area that characterizes the area of the flow field mixing area. As can be seen in the Figure, the shape of the latter mixing zone is even narrower and longer in the same slice. The former still has ethylene with an equivalence greater than 0.2 at the X=70d section, and the latter at the X=45d section, the ethylene isoline no longer intersects the lower wall. It can be concluded that the ethylene injection height is significantly higher than the former, and the pylon effectively weakens the lateral diffusion of the fuel. At the X=35d section, the latter does not have an ethylene component with an equivalence ratio greater than 5.5, but the former also has a large area of high-concentration ethylene components, suggesting that the fin structure accelerates ethylene diffusion. In summary, the pylon can significantly lift the height of the ethylene component in the combustor, increase the penetration depth of the jet, increase the diffusion rate of ethylene, promote the blending of ethylene and incoming streams, and enhance the blending effect. It can not only accelerate the mixing of the fuel with the flow, improve the degree of mixing, thus effectively reducing the length of the combustion chamber, at the same time, also can make the mixture away from the combustion chamber wall, reduce the heat of combustion chamber wall, reducing the material heat resistance requirements.

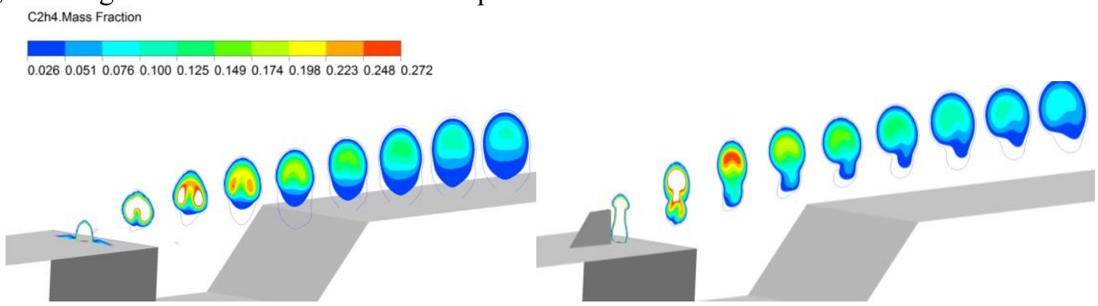

Figure 4. Ethylene mass fraction contour plot in $0.4 \le \Phi \le 5.5$ iso-clip surface and $\Phi = 0.2$ line

For further quantitative analysis of the difference in flow field characteristics of pylon combustor and no-pylon combustor, Figure.5 shows the flow combustible mixing area, plume mass center height, maximum ethylene concentration decay curve, and total pressure loss coefficient curve. From Figure 5(a) we can see that the area of the flammable mixing zone gradually increases in each case. In the case3, the combustible mixing area at the front of the combustor has a faster growth rate, while the later growth is relatively gradual. The overall growth rate of the mixed area of the case1 is not large, and the early growth rate is slow, which is lower than case3, indicating that the pylon can promote fuel blending and diffusion; When reaching near the cavity, the growth rate of combustible mixing area increased rapidly, becoming almost the same as in case 3, and maintained a high growth rate in the later period. This may be that the height of fuel in the case1 is low, and there are many high

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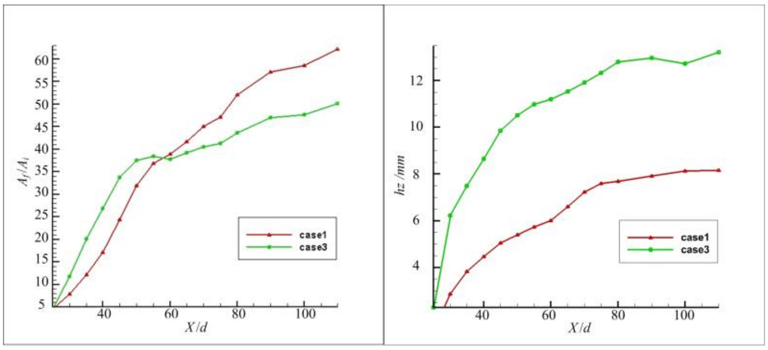
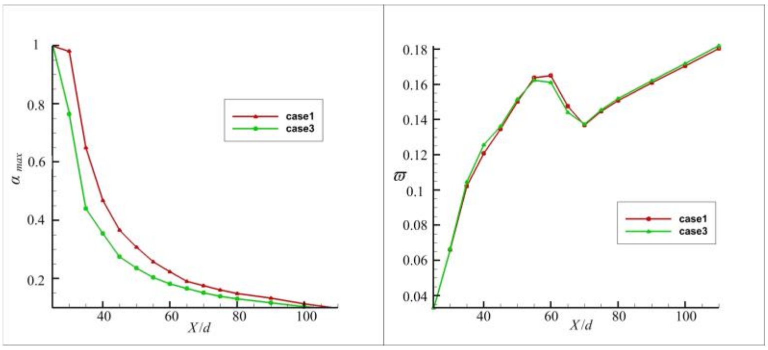
concentrations of ethylene components near the lower wall, as can be seen from the Figure 5 ethylene composition diagram. Therefore, the fuel in the case1 is better to be absorbed by the eddy current in the cavity to increase the diffusion speed.

It can be seen from Figure 5(b) that the mass center height of plume growth of no pylon case are more gently from first to last and the pylon makes jet plume mass center height began to increase rapidly from X=25d. The growth rate became fairly flat around X =50d and the final result was that the latter plume height was much higher than that of the non-pylon structure, which was consistent with the conclusions from previous qualitative analysis. From the Figure 5(c), the ethylene concentration in each case decreases with the flow movement, and the decay rate in the early stage is fast, and the late period is relatively flat. The pylon increases the rate of ethylene diffusion.

From the Figure 5(d),the total pressure loss coefficient curve shows that the two curves basically coincide in the front of the combustor. After X=70d section, the total pressure loss coefficient curve of case3 was higher than that of the case1, but the difference was not significant. Overall, the pylon can not only enhance the penetration depth of the jet, but also enhance the blending of the fuel and the incoming flow. At the same time, it will not bring about a large total pressure loss or distortion of the flow field.



(a) Combustible mixing area (b) Mass center height of plume



(c) Maximum ethylene concentration decay curve (d) Total pressure loss coefficient

Figure 5. Different numerical examples of flow field characteristic parameters

3.2.Influence of cavity on the performance of the scramjet combustor

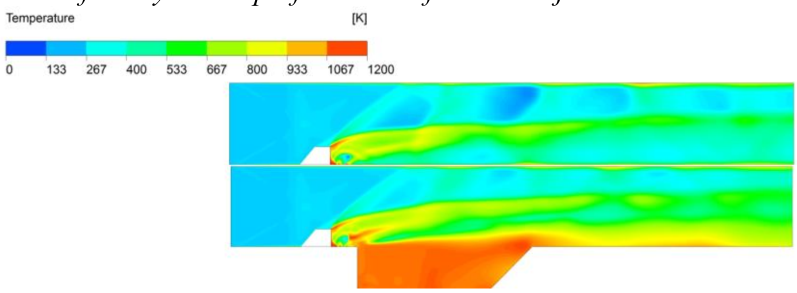


Figure 6. Temperature distribution contours

Figure.6 is a temperature distribution contour of the symmetrical cross-section of the scramjets of case 2 and case 3 under cold flow conditions. It can be seen from the Figure that the temperature inside the chamber of case 3 is significantly higher than that of other areas, which means that the cavity can generate a high-temperature zone by reflow. At the same time, it can be found that the temperature distribution in case 3 is relatively uniform, and there are multiple large-scale low-temperature zones in the case2 combustor. The high temperature area can not only effectively promote the blending of fuel and realize the ignition of the combustion chamber, but also achieve the effect of stabilizing the flame during combustion, which means that the cavity structure can not only promote fuel mixing, but also enhance the flame stabilization ability of the combustion chamber.

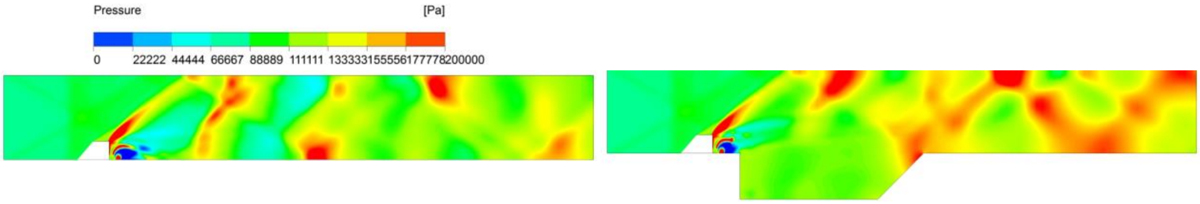


Figure.7 Pressure contours

Figure.7 shows the pressure distribution on the symmetrical section of the combustion chamber. It can be observed that shock waves are generated on the upper edge of the pylon and the shock waves are generated by the wall surface refraction. The comparison shows that the range of the low pressure zone behind the pylon is not much different, but in the cross section X=45d, case3 is a high pressure zone with a relatively small range, and case2 is a band-shaped high pressure zone connecting the upper and lower walls, which may have a great influence on the diffusion of fuel. In the case3, a large-scale shock wave is also generated on the rear wall of the cavity and acts together with the shock wave generated at the pylon. After the wall surface refracts, a shock wave string with a stronger intensity is generated in the combustion chamber, which will inevitably result in greater total pressure loss.

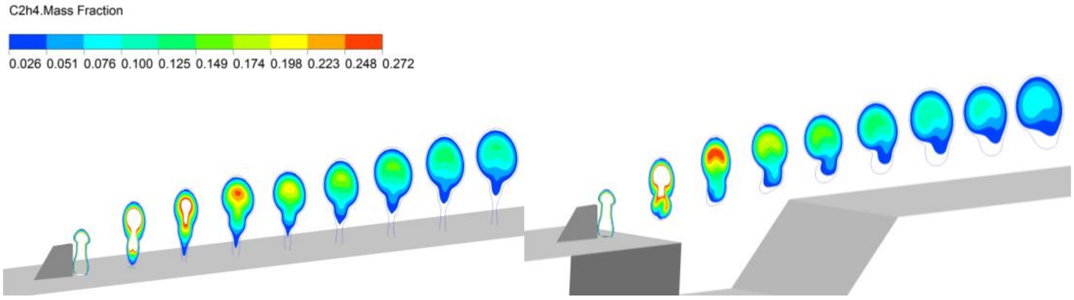


Figure 8. Ethylene mass fraction contour plot in $0.4 \le \Phi \le 5.5$ iso-clip surface and $\Phi = 0.2$ line

To further analyze the influence of the cavity on the performance of the combustion chamber, Figure.8 is a plot of the equivalence ratio of the ethylene composition $0.4 \le \Phi \le 5.5$ and the isoline $\Phi = 0.2$ for cases 2 and 3, respectively. The distribution of fuels in all cases is in the form of a "gourd-shaped". In comparison with Figure 5, it may be due to the pylon. With the gradual transformation of flow field into circle, it can make full use of the channel space and increase the uniformity of fuel distribution in the combustion chamber, which is more conducive to ignition and combustion. On the X=35d section, case3 has no more ethylene components whose equivalence ratio is greater than 5.5, while case2 still has large area of high concentration ethylene components, which indicates that the cavity structure promotes the diffusion of ethylene. Ethylene with an equivalence ratio greater than 0.2 is always present on the lower wall of the combustor, and the ethylene isoline of case 3 no longer intersects with the lower wall surface after injection. It can be known that the cavities can significantly raise the height of lean components in the combustion chamber. It is worth noting that the lower part of the case 2 component chart is more tapered, while case 3 is more slick, which may be due to the effect of retraction of the cavity.

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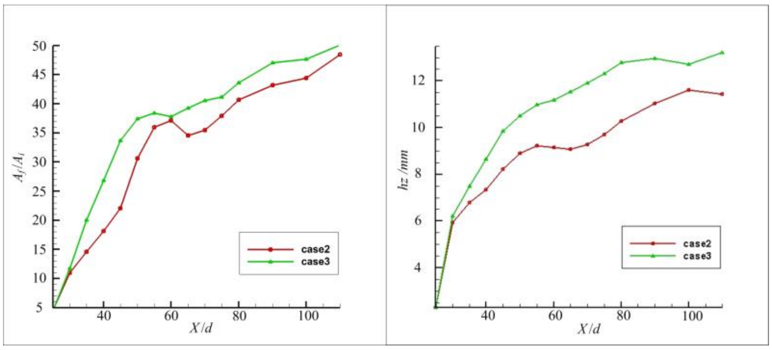
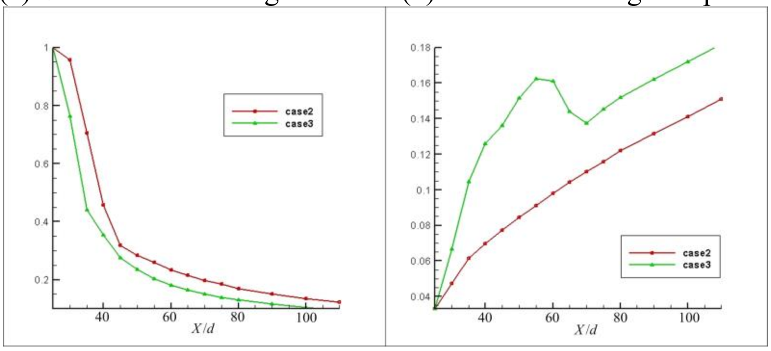


(a) Combustible mixing area (b) Mass center height of plume



(c) Maximum ethylene concentration decay curve (d) Total pressure loss coefficient

Figure 9. Different numerical examples of flow field characteristic parameters

To quantitatively analyze the influence of cavity on jet penetration and blending, Figure.9 shows the area of the combustible mixing zone in the flow field, the plume center height, the maximum ethylene concentration decay curve, and the total pressure loss coefficient curve. As obtained by Figure 9(a), the area of the combustible mixing area is gradually increased. In the early period, the growth rate did not differ significantly. In the vicinity of cavity, the growth rate of case 3 was significantly higher than that of case 2. In the latter half of the combustion chamber, the growth rate of the combustible mixture area was not much different, indicating that cavity promoted the diffusion of ethylene component. This may be due to the suction effect of the cavity, so the former ethylene blending effect is poor, consistent with the previous qualitative analysis conclusions. As we can see from Figure 9(b), with the flow movement, the height of the mass center of the plume is increased gradually. The initial growth rate of the two case is consistent. Case 3 was significantly higher than case 2 in the vicinity of the cavity, and remained almost constant in the later period. This is similar to the change trend of the combustible mixing area, indicating that the cavity increases the penetration depth of the jet.

It can be seen from Figure 9(c) that the ethylene concentration in each case decreases with the flow. The decay rate is fast in the early stage and relatively gentle in the later stage. The addition of cavity structure increases the rate of ethylene diffusion. Figure 9(d) shows that the trends of case 2 and case 3 in the total pressure loss curve of the rear section of the combustion chamber are almost the same. The total pressure loss near the concave cavity suddenly increases, which is obviously larger than that of the former. It may be caused by the strong shock wave generated by the back wall of the concave cavity, which is consistent with the conclusion obtained from the previous analysis of pressure cloud diagram. In conclusion, cavity has a significant effect on improving the penetration depth and mixing of the combustion chamber. Next step is to further optimize length to depth ratio or the posterior wall inclination of cavity to reduce total pressure loss and improve the performance of scramjet engine.

4.Conclusion

In this paper, the qualitative and quantitative research is conducted from the aspects of fuel distribution, mixing efficiency, and total pressure loss to discuss the advantages of the combination of pylon and cavity. The conclusions are drawn as follows:

1）Pylon can not only enhance penetration depth of the jet, but also enhance the blending of fuel and incoming flow, and it does not bring about a large total pressure loss or distortion of the flow field.

2）Cavity can promote the diffusion of ethylene and increase the penetration depth of fuel, but it causes a large total pressure loss.

3）The combination of pylon and cavity can make good use of the advantage of the each single device and the geometry dimension and the combination mode of the pylon and cavity can be further analyzed from to improve the performance of the scramjet engine in next step.

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