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OVERVIEW OF FUEL INJECTION TECHNIQUES FOR SCRAMJET ENGINES

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ABSTRACT

As one of the most promising hypersonic propulsion systems for hypersonic vehicles, the scramjet engine has drawn an ever increasing attention of researchers worldwide. At present, one of the most important issues to be dealt with is how to improve the fuel penetration and mixing efficiency and make the flame stable in supersonic flows. Further, how to reduce the structural weight of the engines is an urgent issue that needs to be considered. The ongoing research efforts on fuel injection techniques in the scramjet engine are described, mainly the cavity flame holder, the backward facing step, the strut injection and the cantilevered ramp injection, and the flow field characteristics and research efforts related to these fuel injection techniques are summarized and compared. Finally, a promising fuel injection technique is discussed, namely a combination of different injection techniques, and the combination of the cantilevered ramp injector and the cavity flame holder is proposed. This is because it can not only stabilize the flame, but also shorten the length of the combustor, thus lighten the weight of the scramjet engines.

INTRODUCTION

Since the X-43A was flight tested successfully twice in 2004 (Mach number 6.83 on March 27 & Mach number 9.68 on November 16) [1, 2] and the X-51A was flight tested successfully with power for the first time at Mach number 5.0 on May 26, 2010[3-5], the hypersonic airbreathing propulsion technology has drawn an ever increasing attention of many researchers. Although the duration time for the powered flight of the X-51A (>200s) is much longer than that of the X-43A (≈12s) [6], this does not meet the initial purpose of this project (≈300s). At the same time, the residence time of the fuel staying in the supersonic flow is very short, namely of the order of 1ms[7-9], and how to reduce the ignition delay time, to improve the fuel penetration and mixing efficiency and to provide a continuous source of hot radicals for the chemical reactions, is an important issue for researchers worldwide. In order to solve this problem over the past few years, many fuel injection techniques have been proposed, namely, fuel injected from a wall orifice transversely[10], a backward facing step followed by transverse injection[11-17], angled injection, swept ramp injection[18, 19], aerodynamic ramp injection[20, 21], strut injection[22-28], pylon injection[29-31], cantilevered ramp injection[32-34] and cavity flame holder[7, 35-45] which integrates the fuel injection and the flame holding capabilities together. In the open literature, Deepu et al.[46] reviewed the mixing penetration and combustion characteristics of the injected fuel and incoming air stream in scramjet engines for different kinds of injectors. At the same time, the combination of different fuel injection techniques[3, 44, 47, 48] is employed in the scramjet engines, and the flow field characteristics and research efforts need to be summarized and discussed, thus the researchers can obtain comprehensive knowledge on the fuel injection techniques in supersonic flow.

Further, in order to improve the aero-propulsive performance of hypersonic vehicles, the airframe/engine integration technology has been brought forward, which employs the forebody of the airframe to pre-compress the supersonic inflow and uses the afterbody of the airframe as one part of the nozzle to further expand the exhaust jet stream[49]. However, due to the low integrated level, the cruising performance of the vehicle cannot satisfy the requirement of

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the researchers, and the forebody injection strategy[50, 51] has been proposed and employed in the hypersonic propulsion system which uses the cantilevered ramp injection as the fuel injector. This strategy can shorten the length of the combustor, lighten the structural weight of the engine, maintain a better performance over a broad range of flight Mach numbers and improve the integrated level between the airframe and the engine[8]. Further, it is a promising choice to break through the development bottleneck of the scramjet engine and improve the performance of hypersonic vehicles. However, the geometric configuration of the inlet/forebody must be reconstructed to prevent premature ignition of the premixed combustible flow according to the geometric configuration of the cantilevered ramp injector.

Based on an integral design of hypersonic vehicles, this paper describes the ongoing research efforts on fuel injection techniques in scramjet engines, mainly the cavity flame holder, the backward facing step, the strut injection and the cantilevered ramp injection, and the flow field characteristics and research efforts related to these fuel injection techniques are summarized and compared. Finally, a promising fuel injection technique is discussed, namely a combination of different injection techniques, and the combination of the cantilevered ramp injector and the cavity flame holder is proposed, since it can not only stabilize the flame in supersonic flow, but also shorten the length of the combustor, thus lighten the weight of the hypersonic propulsion systems.

CAVITY FLAME HOLDER

Ben-Yakar et al.[35] summarized the ongoing research efforts on cavity flame holders, and pointed out the important research issues which must be solved urgently. According to the magnitude of the length-to-depth ratio, the cavity flow can be categorized into two basic flow regimes. For L/D < 7-10, the cavity flow is termed to be "open" because the upper shear layer reattaches to the downstream trailing edge, and for L/D > 10-13, the cavity flow is termed to be "closed" because the free shear layer reattaches to the floor face. The closed cavities are characterized by a larger drag coefficient compared with open cavities[9].

Huang et al.[7] investigated the effect of the location of the fuel injection on the combustion flow field of a typical hydrogen-fueled scramjet combustor with multi-cavities, and the length-to-depth ratio of the cavity is 5.0. Kim et al.[9] discussed the effect of the cavity configuration, i.e. the aft wall angle, the offset ratio of upper to the downstream depth and the length, on the combustion efficiency and the total pressure loss in the scramjet engines. Further, Rasmussen et al.[40] used visual observations, planar laser-induced fluorescence of nitric oxide and shadowgraph imaging to examine the stability of hydrocarbon-fueled flames in cavity flame holders in supersonic flows, and Alam et al. [41] examined the effectiveness of controlling cavity pressure oscillations by employing a sub-cavity on the upstream leading edge of the cavity with a flat plate. Lee et al. [42] and Bres et al. [45] used direct numerical and large eddy simulations to investigate the influence of the incoming turbulent boundary layer on the self-sustained oscillations of the shear layer over open cavities, and Fig.1 illustrates the time-averaged streamlines of turbulent flows over deep and shallow cavities with different length-to-depth ratios. Fig.2 shows a comparison of the time-averaged flow streamlines for different Reynolds numbers, namely 3000 and 12000.

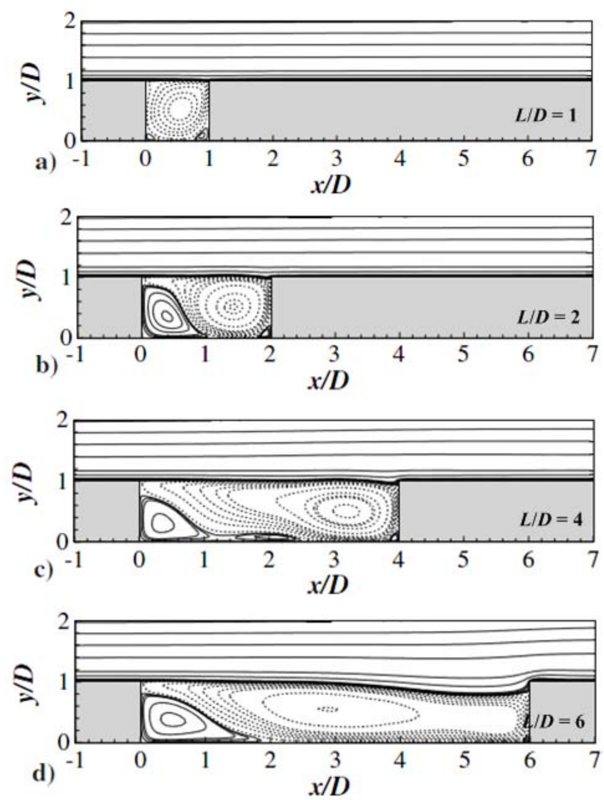


Figure 1. Time-averaged streamlines of turbulent flows over open cavities with different length-to-depth ratio [42].

A two-component particle image velocimetry system, surface flow visualization, mean and time-varying surface pressure measurements and an unsteady Reynolds-average Navier-Stokes code with a realizable k-ε turbulence model were employed to perform a transonic flow simulation over an open cavity. At the same time, the effect of the aft wall angle on the strength of the acoustic wave in open cavities was studied experimentally by Vikramaditya et al. [37], and statistical methods were employed to perform the data analysis. Further, Huang et al. [38] combined the numerical method and the statistic theory to investigate the effect of cavity configuration on the aero-propulsive of the integrated hypersonic vehicle. These illustrate that the application of the statistical method in the aerospace propulsion system is a trend in the following few years since it can improve the design efficiency and reduce the cost.

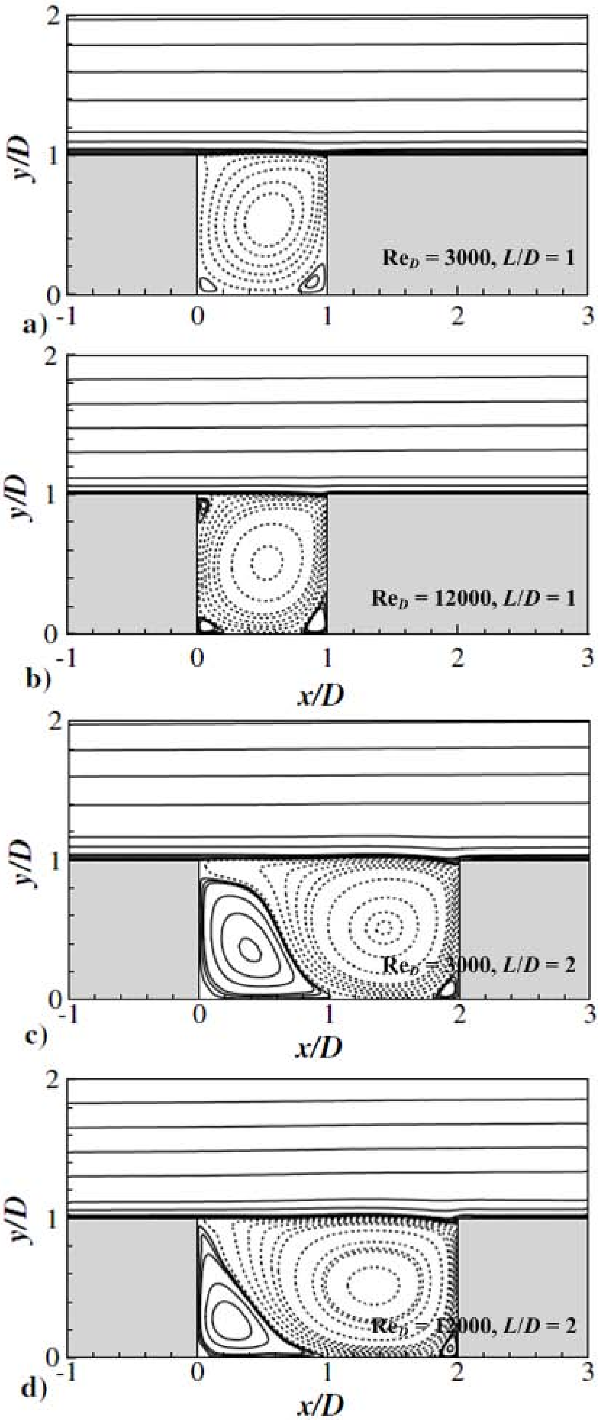


Figure 2. Comparison of time-averaged flow streamlines at Re$_D$ = 3000 and 12000 [42].

BACKWARD FACING STEP

Fig.3 illustrates a schematic of the flow field characteristics over a backward facing step. The incoming boundary layer separates at the leading edge of the step because of the sudden change in the geometric configuration, and a recirculation zone and a corner eddy are generated in the vicinity of the step. Subsequently, the shear layer impinges onto the bottom wall of the channel, and a reattachment shock wave is formed. The recirculation zone and the corner eddy are beneficial for ignition and the stabilization of the flame in the supersonic flow. This is because the velocity in this region is much lower than anywhere else, and the fuel can remain in the supersonic flow for a long time.

Tihon et al.[11] investigated the near-wall flow organization by mapping the fluctuations in the wall shear rate downstream of the step, and they mainly focused on the transient flow regime in the backward facing step flow.

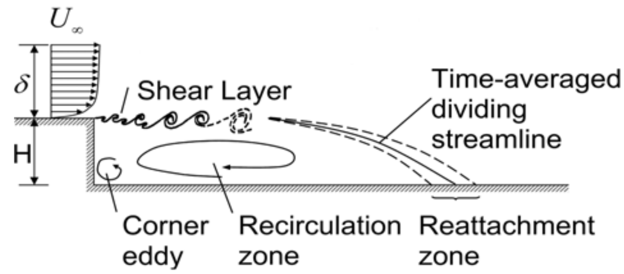


Figure 3. Schematic of the backward facing step flow.

Takahashi et al.[12] employed a three-dimensional full Navier-Stokes numerical code with a large-eddy simulation turbulence model and a detailed chemical reaction model to clarify whether the self-ignition and transition to flame-holding are dominated by the near-field or far-field phenomena in a rectangular scramjet combustor with a backward step. Further, a DES method was introduced to investigate the reactive flows in a backward facing step, namely the Delayed Detached Eddy Simulation (DDES), and the numerical results show good agreement with the experimental data[14]. At the same time, Khan et al.[15] examined the time-dependent behavior of shock wave/boundary-layer interactions numerically for flows over a backward-facing step, and the effects of an applied magnetic field over the unsteady nature of the problem were explored.

Chen et al.[52] used a numerical method to explore the effects of step height on turbulent separated flows and the heat transfer over a backward facing step, and Fig.4 shows the general flow characteristics for different step heights. In Fig.4, ER is the expansion ratio, and S is the channel's reference height (= 0.038m). They found that the primary recirculation region increases adjacent to the step after the boundary separation with the increase of the height of the step and the shear layer impingement onto the bottom wall of the channel[52]. Meanwhile, Halupovich et al.[53] investigated the effects of the incoming boundary layer, Reynolds number and inlet Mach number on the flow field over a backward facing step, and they found that the numerical results show good qualitative agreement with experimental data at moderate supersonic free stream Mach numbers, namely Ma < 3.5.

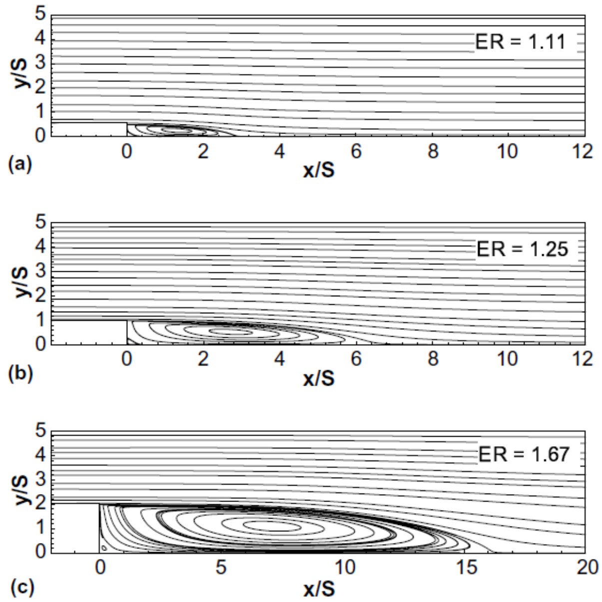


Figure 4. Flow characteristics for different step heights[52].

Further, Tinney[54] used a combination of both quantitative measurements from a particle image velocimetry (PIV) system and qualitative oil-flow visualizations to investigate the flow field over a three-dimensional double backward-facing step. Fig.5 illustrates the flow field characteristics over the three-dimensional double backward facing step.

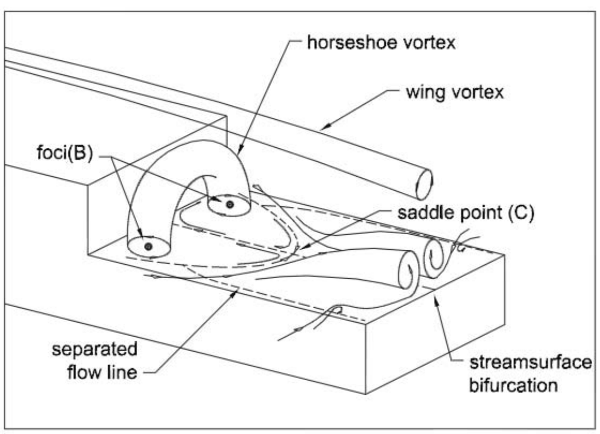
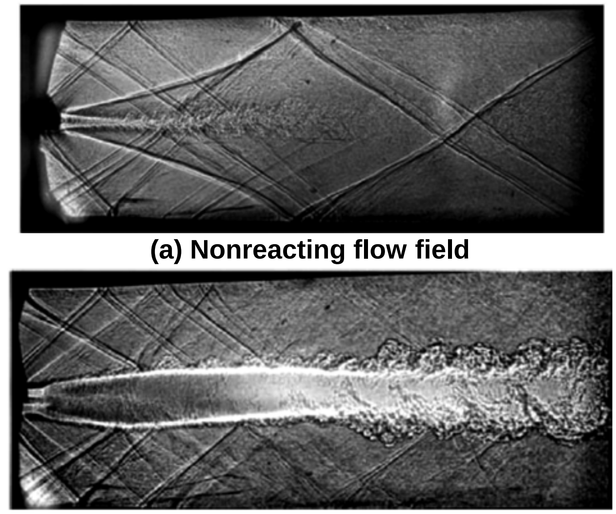


Figure 5. Schematic of the flow field characteristics over a three dimensional backward facing step[54].

STRUT INJECTION

Fig.6 shows the nonreacting and reacting flow field characteristics of the strut, and two clear oblique shock waves are generated at the tip of the strut. Shock waves and expansion waves exist in the flow field of the strut simultaneously, and there are a pair of eddies formed in the vicinity of the base surface of the strut, which acts to stabilize the flame, see Fig.7.



(a) Nonreacting flow field

(b) Reacting flow field

Figure 6. Experimental Schlieren image of the flow fields in the vicinity of the strut[23].

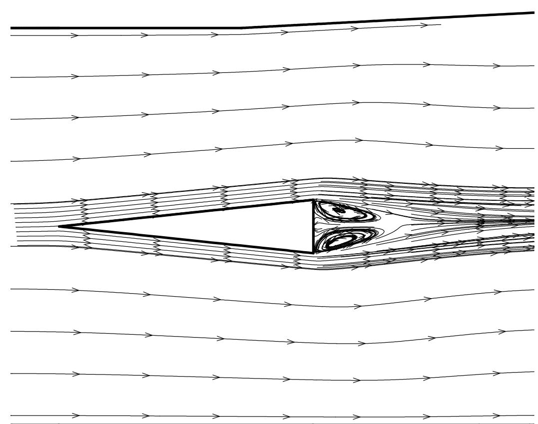


Figure 7. Local streamline path around the strut.

Zou et al.[26] validated the newly-proposed partially resolved numerical simulation (PRNS) procedure in the simulation of the flow fields in the two-dimensional strut-based scramjet combustor. Dinde et al.[28] employed the realizable k-ε model in FLUENT to simulate the nonreacting and reacting flow fields in the three-dimensional strut-based scramjet combustor. Further, Luo et al.[27] compared the feasibilities of different turbulent models in the simulation of the flow fields of the two-dimensional strut-based scramjet combustor, namely the RNG k-ε model, the realizable k-ε model and the SST k-ω model. At the same time, they employed three different grid scales to verify the grid independence.

In order to observe the refined flow field structures in the strut-based scramjet combustor, the large eddy simulation method was introduced to further model the flow fields[23, 25]. Meanwhile, Oevermann[24] developed an implicit finite volume method for the computation of turbulent diffusion flames in the compressible flow fields of the strut-based scramjet combustor, and this method uses a two equation *k-ε* turbulent model combined with a stretched laminar flamelet model.

CANTILEVERED RAMP INJECTION

The cantilevered ramp fuel-injection strategy is considered as a means to deliver rapid mixing for use in hypersonic propulsion systems, namely the scramjet and the shcramjet, and it is thought to embody the characteristics of both conventional ramp and low-angle wall injection techniques[34], see Fig.8. Fig.8 shows a schematic of the cantilevered ramp injection flow. At the same time, the cantilevered ramp injector is a very promising fuel injection method for the shock-induced combustion ramjet (shcramjet) engine, and this engine is the most promising candidate for improving the airframe/engine integrated design level in hypersonic vehicles. At the same time, it can break through the choke point of the technique development in scramjet engines. However, in the application process, a severe problem must be solved, namely preventing premature ignition of the premixed combustible flow in the forebody/inlet[55].

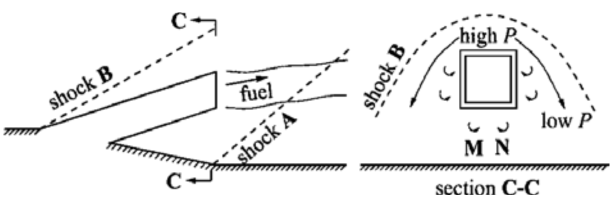


Figure 8. Schematic of the cantilevered ramp injection flow[34].

In the open literature, Turner et al. [50] first employed the inlet injection strategy in the scramjet engine to determine the feasibility of reducing the combustion-chamber length through experiments, and they found that there was no evidence of combustion in the inlet.

Parent et al.[34] employed the Favre-averaged Navier-Stokes equations to investigate the influence of the convective Mach number and the global equivalence ratio on the mixing efficiency of the cantilevered ramp injection, and then they investigated the effects of the injector array spacing, injection angle and sweeping angle at a fixed convective Mach number on the fuel penetration and mixing efficiency in the supersonic flow, namely the convective Mach number is 1.5[32].

COMBINATION OF DIFFERENT FUEL INJECTION TECHNIQUES

The cavity flame holder can prolong the residence time of the fuel in the supersonic flow. However, it cannot improve the fuel penetration and mixing efficiency. At present, in order to utilize the advantages of different fuel injection techniques, researchers have started to combine several fuel injection techniques in the supersonic combustion, e.g. the combination of the cavity flame holder and the strut[44, 47], the combination of the cavity flame holder and the backward facing step[48]. At the same time, the combination of different fuel injection techniques is another proper choice to break through the choke point of the technique development in scramjet engines. Fig.9 illustrates a schematic of a typical combination of different fuel injection techniques in the scramjet engine, namely the integration of the strut and the cavity.

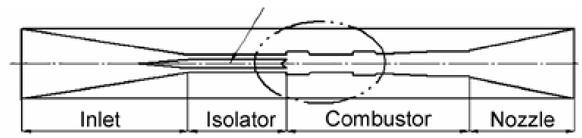


Figure 9. A schematic of the combination of the cavity flame holder and the strut in the scramjet engine[44].

In order to compare the effects of the different flame holding mechanisms on the flow field characteristics in supersonic flows, Huang et al. [3] employed numerical methods to generate the flow field structures in scramjet combustors with a backward facing step and a cavity flame holder. Further, Zhao et al. [48] experimentally investigated the effect of back pressure on the shock wave train movement in a typical scramjet combustor which combines the backward facing step with the cavity as the flame holding mechanism.

At the same time, Gu et al. [44] and Yu et al. [47] experimentally tested a scramjet model with strut/cavity integrated configurations in order to improve the engine performance, and Gu et al. [44] found that the strut can serve as an effective tool in a kerosene-fueled scramjet. Further, the integration of strut/cavities had great effect on stabilizing the combustion over a wide range of fuel equivalence ratios. However, this fuel injection technique brings more drag force to the scramjet engine and increases the structural weight of the engine. Thus, the combination of the cantilevered ramp injection and the cavity flame holder is proposed, so that it can reduce the weight of the engine, to a certain extent. At the same time, this technique can improve the fuel penetration and mixing efficiency in the supersonic flow. In the open literature, few researches have focused on this topic.

SUMMARY AND CONCLUSIONS

In this paper, the ongoing research efforts on several fuel injection techniques in scramjet engines have been described, mainly the cavity flame holder, the backward facing step, the strut injection and the cantilevered ramp injection. Finally, as an effective fuel injection technique in supersonic flows, a combination of different fuel injection techniques has been discussed, and the combination of the cantilevered ramp injector and the cavity flame holder has been proposed. We observe the following:

- The fuel injection techniques employed in the hypersonic propulsion systems can generate recirculation zones and eddies in the vicinity of these configurations, and these flow field characteristics make a large difference to the improvement in the flame stabilization, the fuel penetration and the mixing efficiency in supersonic flows.

- The investigation of pressure oscillations and geometric parametric influences on the performance of the cavity is drawn an ever increasing attention, and multi-cavities are employed in supersonic flows to improve the performance of the scramjet engine.
- The combination of several fuel injection techniques is a promising trend for hypersonic propulsion systems, and it embodies the advantages of different fuel injection techniques. In the future, in order to improve the fuel penetration, the mixing efficiency, the flame stabilization and the airframe/engine integration design level of the hypersonic vehicles, lighten structural scramjet engines, combined with a cantilevered ramp injector and a cavity flame holder is a most promising trend for hypersonic propulsion systems. This will prolong the residence time of the fuel staying in the supersonic flow and shorten the length of the combustor.
- More complex numerical methods are employed in the nonreacting and reacting flow fields, from RANS to LES, and then from LES to DES. At the same time, more complex combustion models will be introduced to model the flow fields in supersonic flows, namely the flamelet and the PDF.
- In the next few years, the application of statistical methods in hypersonic propulsion techniques is a promising trend, and this would improve the design efficiency and reduce the cost.

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