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Research status of key techniques for shock-induced combustion ramjet (shcramjet) engine

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As one of the most promising propulsion systems in the future, shock-induced combustion ramjet engine can remedy the disadvantages in the integrated design of scramjet engine and airframe. It can shorten the length of the combustor, lighten the structure weight of the engine and keep better performance in a broad range of flight Mach number. The elementary principle of shock-induced combustion ramjet engine is introduced. The key technologies of this kind of propulsion system are described, while their research status is presented in detail. Suggestion on the development of shcramjet engine in China is put forward.

aerospace propulsion system, shock-induced combustion ramjet engine, premature ignition, premixed efficiency, denotation

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1 Introduction

The mixing and diffusive combustion of fuel and air in conventional scramjet engines take place simultaneously in the combustor. However, the incoming supersonic flow can stay in the combustor only for a very short time, which will restrict the scramjet engine design. A much longer combustor is required for the fuel and air to be mixed and combusted efficiently and completely, but will increase the structure weights of the engine and the coolant system sharply, and restrict the improvement of the vehicle performance, especially when the flight Mach number increases further.

Shock induced combustion ramjet (shcramjet) engine organizes combustion by detonation, so the reactive distance is very short and the length of the combustor is shortened accordingly. Therefore, the structure weight of the engine and the coolant system is reduced, as well as the loss brought by wall friction. At the same time, the range of the flight Mach number of shcramjet engine will be expanded to break through the upper limit of that of hydrocarbon fueled scramjet engine while keeping a better performance. The entropy production and total pressure loss will be reduced greatly by CJ oblique detonation, and the thrust performance of the engine can be optimized. Results [1] obtained with the flight Mach numbers $12 \leqslant M_\infty \leqslant 16$ and a flight dynamic pressure of 67032 Pa showed that the thrust of a shcramjet is maximized when the temperature at the entrance of the combustor is between 650 and 700 K, where the combustion is entirely shock induced. Meanwhile, compared with detonation wave ramjets, the thrust production and fuel specific impulses of shcramjet can be improved by 10% and 33.3%, respectively.

Couture et al. [2] studied the performance of scramjet and shcramjet powered vehicles comparatively with the same external aerodynamic envelope and the same combustion efficiency. It was found that these two schemes have approximately the same performance. However, the shcramjet scheme has higher base drag and needs slightly

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more fuel to obtain the same force balance.

Only a few countries have done some researches in the field of shcramjet engine so far, i.e., Canada and the United States. The presented paper attempts to discuss the research situation according to the oversea research status of the key techniques of shcramjet engine, and provides guidance for this technique in our country.

2 Basic principle

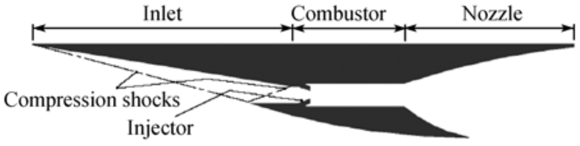
Shock-induced combustion ramjet engine is a new conceptual propulsion system which is similar to conven- tional scramjet engines using airframe/engine integrated design, as shown in Figure 1. The oblique plane below the leading portion of the airframe is designed as an external compression or mixing-compression inlet, where the inflow is compressed. The combustor locates in the lower part of the middle section, and the posterior segment is the nozzle. Fuel is injected at the forebody/inlet, with methods to enhance the mixing efficiency of fuel and air before their entry into the combustor. Then a normal shock wave is generated by the wedge or blunt body in the front of the combustor, which ignites the supersonic mixture rapidly. This ignition and combustion mode is called shock-induced combustion.

Within the external compression inlet, the first equal-strength shock wave AC is generated by the first oblique plane AB, while fuel is injected into the compressed supersonic flow in the inlet. Fuel and air are mixed behind the first equal-strength shock AC, and the temperature of the fuel/air mixture is maintained below 900 K (the auto-ignition temperature for hydrogen). The second equal-strength shock wave from B to C (lip of the cowl) is generated by the second oblique plane BE. This shock enhances the mixing of fuel and air, and compresses the flow further, which raises the temperature of the flow to above 900 K. Then the mixture is ignited, and a detonation wave EC is generated at the entrance of the combustor, which ignites the mixture across the wave immediately. The completely burnt gas passes through section EF and exhausts by a diverging nozzle which provides the thrust, as shown in Figure 2.

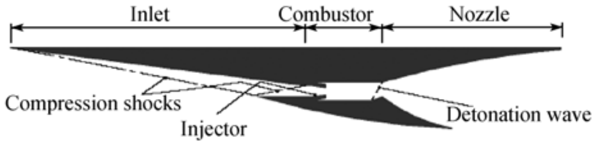
The key point of shcramjet engine design is to make the fuel/air mixed sufficiently before entering the combustor, and the duration of combustion is only controlled by chemical reactions. The shock wave used to ignite the mixture will increase the temperature of the mixture and accelerate the reactions. Adequate radicles are generated with the temperature rise and recombined into productions, which releases a mass of heat. This process is defined as flame front. The reaction time of shock induced combustion will descend when the temperature rise of the shock wave increases drastically, which will reduce the distance between the shock wave and the flame front greatly. If the shock wave is strong enough and the reaction proceeds more rapidly, the flame front will be coupled with the shock wave, and the detonation wave is formed.

3 Key techniques

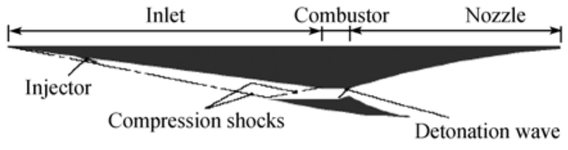
The application foreground of shcramjet engine, which can accelerate the heat release, reduce the loss of the inlet, decrease the combustor dimensions, and thereby lighten the integral weight of the engine and coolant system, is remarkable in the level of performance estimation. However, in the level of technique implementation, there are many key technologies to be broken through, including experimental validation of stable detonation, mixing, prevention



(a) Conventional scramjet

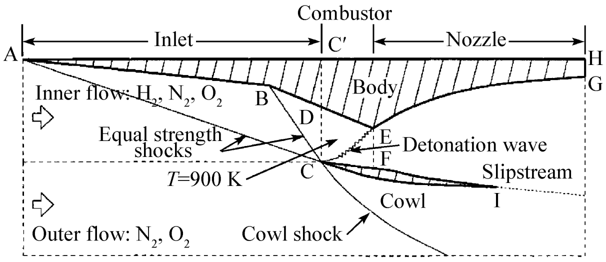


(b) Internal injection shcramjet

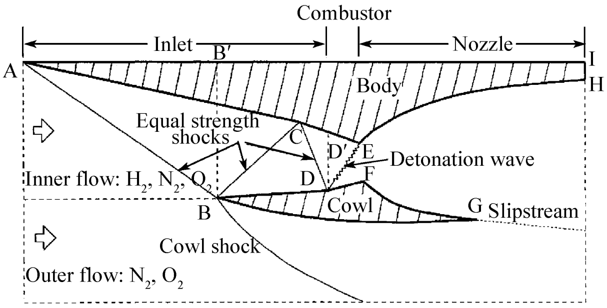


(c) External injection shcramjet

Figure 1 Hypersonic airbreathing vehicle schemes [3].



(a) External compression



(b) Mixed compression

Figure 2 Shcramjet model [4].

of premature ignition in the upstream and the boundary layer, prevention of boundary layer separation, and actual performance estimation of the engine.

To validate the feasibility of shcramjet engine, researches must seriously address the tasks: 1) achieving adequate fuel/air mixing before the combustion, and 2) preventing premature ignition of the premixed combustible flow in the forebody/inlet [5].

At the same time, it is a key issue to carry out the direct detonation initiation and keep stable combustion in the premixed hypersonic flow.

3.1 Fuel/air premixing

Usually, the fuel injected at the forebody/inlet of the vehicle will change the wave structure, which will prevent the leading shock waves from intersecting on the lip of the cowl, and the performance of the propulsion system will be deteriorated. So the forebody/inlet configuration must be redesigned to satisfy the performance requirements of the propulsion system.

In order to improve the premixed performance, Sislian and Schumacher [6] put forward an injector geometry, which embodies the characteristics of both conventional ramp and low angle wall injection techniques, referred to as a cantilevered ramp injector， as shown in Figure 3. Numerical results showed that the mixing performances of the cantilevered ramp injector are appreciably superior to those of the conventional ramp injectors. On the flow conditions considered in ref. [6], its mixing efficiency is about 45% higher than that of the conventional ramp at x=0.8 m downstream of the injector exit with an approximately 20% penalty in the total pressure loss.

Moreover, Parent and Sislian [8] investigated the turbulent hypersonic fuel/air mixing characteristics of cantilevered ramp injectors by numerical simulations, which focused on the influences of convective Mach number. Results showed that the mixing efficiency varied by 31% for a convective Mach number ranging from 0 to 1.5 while the associated mass average stagnation pressure varied by only 10%. It is obviously advantageous to enhance the mixing of fuel and air by increasing the convective Mach number. At the same time, Parent and Sislian [9,10] investigated the effects of the injector array spacing, injector angle and sweeping angle on the mixing efficiency at a convective Mach number of 1.5, and discussed the mixing enhancement induced by the axial vortices of the cantilevered ramp injectors. Results showed that an air cushion between the wall and the hydrogen was sufficiently thick to prevent the fuel from penetrating the boundary layer when 1) the injection angle was no less than 10°, 2) the array spacing was no less than the height of the injectors used, and 3) a swept ramp configuration was avoided.

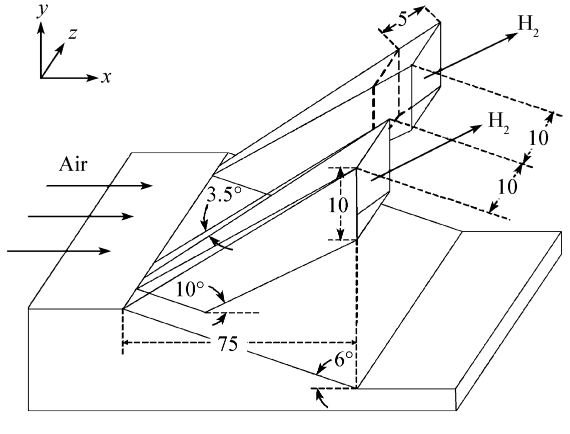


Figure 3 Optimized cantilevered injector geometry [7].

Sislian et al. [11] and Redford [12] investigated the effects of incomplete fuel/air mixing and off-design flight conditions on the performance of shcramjet engine. Results showed that incomplete mixing led to a combination of detonation and shock-induced combustion. The propulsive properties of the engine were deteriorated when it was operated at off-design conditions. Mixed-compression ramjets were found to provide superior off-design performance to external-compression ramjets which were more sensitive to off-design operation. When operating at lower-than-design Mach numbers, the degradation in thrust production is primarily due to reduction of heat release in the nozzle for mixed-compression ramjets. Whereas for external-compression ramjets, it's due to a high-pressure zone created in the combustor by the impingement of the detonation wave on the engine surface upstream the design point. At higher-than-design Mach numbers, thrust production is reduced slightly due to a modified nozzle.

In order to improve the premixed efficiency of fuel and air further, Alexander et al. [13] investigated the effect of relative array locations by moving the cantilevered ramp injector to the forward section of the mixing duct and using cantilevered ramp injector arrays on opposite inlet walls, as shown in Figures 4–6. Results showed that the premixed efficiency was improved obviously. Non-reactive mixing efficiency up to 0.58–0.68 was achieved with thrust potential loss less than that gained from high-speed fuel injection. Reactive mixing efficiency was up to 0.46–0.54, while an air buffer created between the fuel and walls suppressed premature ignition effectively.

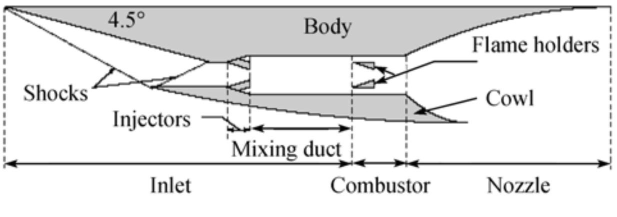


Figure 4 Mixed-compression shcramjet engine [13].

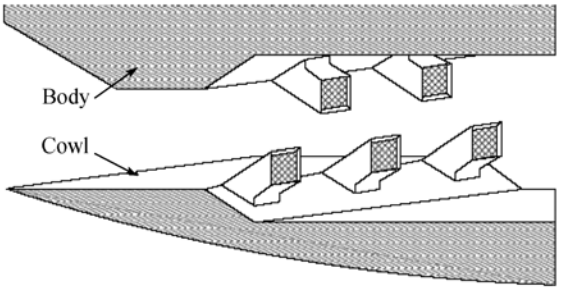
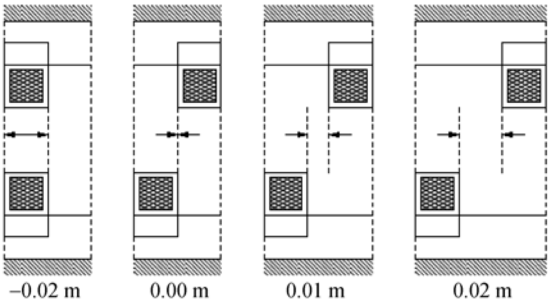
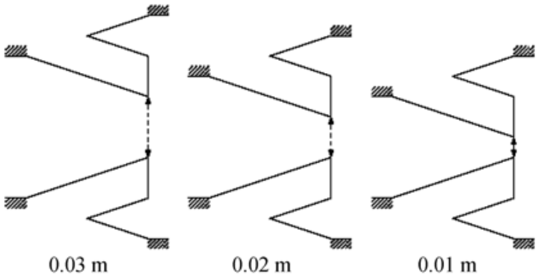


Figure 5 Injector arrays on opposing duct walls [13].



(a) Changes in array displacement



(b) Changes in array separation

Figure 6 Opposed injector array geometry changes [13].

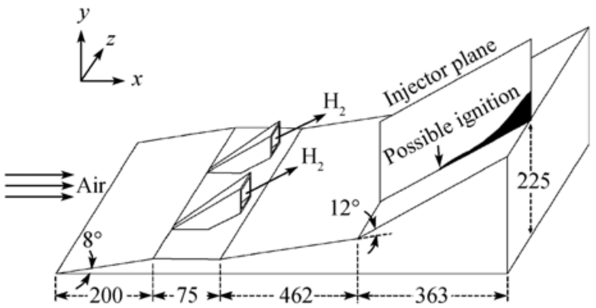


Figure 7 Baseline dual-spike shcramjet inlet [7].

Alexander and Sislian [14] investigated the three-dimensional shcramjet flow field at flight Mach 11 and a flight altitude of 34.5 km using this kind of fuel injector configuration, and a fuel specific impulse of 683 s was obtained.

3.2 Premature ignition suppressing

The mixing process of the fuel and air in the hypersonic flow in the forebody/inlet may cause premature ignition easily for the mixtures in the hot boundary layer, as shown in Figure 7. The cantilevered ramp injectors succeeded in keeping the fuel/air mixture out of the boundary layer until the last 15% of the inlet [15]. However, at the point where the second inlet shock wave compresses the mixture into the boundary layer, the mixture ignites and spreads quickly into the core flow before the inlet exit, and premature ignition arises.

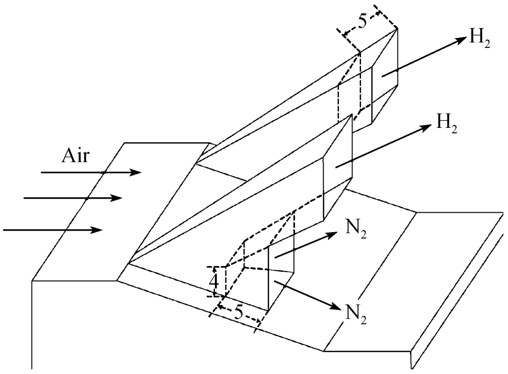
Turcu [15] investigated the flow field in the immediate vicinity of two configurations of cantilevered ramp injectors by numerical simulation, and the probability of premature ignition in the fuel/air mixing process was discussed. The analysis of the numerical solutions showed that premature ignition occurred for both configurations, where the fuel was ignited by the hot air rising from the boundary layers. Sussman [16] investigated the ignition of H_2 in air in the boundary layers of high-enthalpy hypersonic flows by numerical simulation, and the effects of the wall temperature and the equivalence ratio of the ignition process were discussed with a Mach number range between 2 and 17.

Schwartzentruber et al. [17] ascertained the location of premature ignition. Gaseous nitrogen and additional hydrogen were injected into the inlet flow field in an attempt to suppress the flame. At the same time, he minimized the amount of coolant gas necessary to prevent premature ignition, while not deteriorating the performance of the inlet.

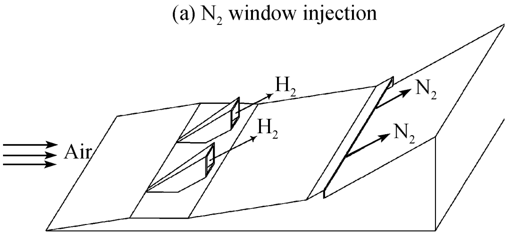
Results showed that among the schemes of suppressing premature ignition in the inert flow filed, as shown in Figure 8, the first scheme didn't cool the boundary layer. On the contrary, the air with high temperature would spread into the core flow from the boundary layer. In contrast, both the post-shock and pre-shock slot injections succeeded in cooling the boundary layer significantly. By injecting nitrogen prior to the shock, it had a longer distance to mix the fuel/air and cool the boundary layer. In addition, the pre-shock strategy injected nitrogen at a much lower pressure which corresponded to approximately 60% less nitrogen (by mass) than the post-shock strategy. Each strategy was verified to have a negligible effect on both the mixing efficiency and skin friction losses.

Although premature ignition was suppressed by inert gases successfully, it was complex to carry a separate tank of cryogenic nitrogen in applications. Then reactive flow field was discussed. Although hydrogen injection would create a new combustible flow region, premature ignition would not occur as the temperature was below that required for ignition. Moreover, Schwartzentruber used an array of expansion ramp injectors, as depicted in Figure 9, instead of a continuous slot injector to reduce the mass flow of additional hydrogen and it suppressed premature ignition.

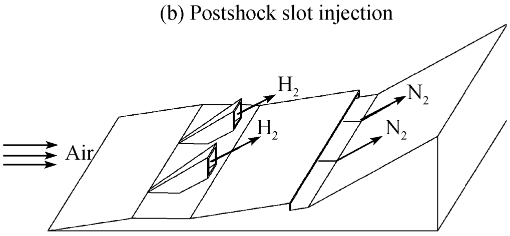
In available literature, Sislian et al. [18] did the first proof of the feasibility of this hypersonic propulsion concept in



(a) N_2 window injection



(b) Postshock slot injection



(c) Preshock slot injection

Figure 8 Three strategies of the inert flow field [17].

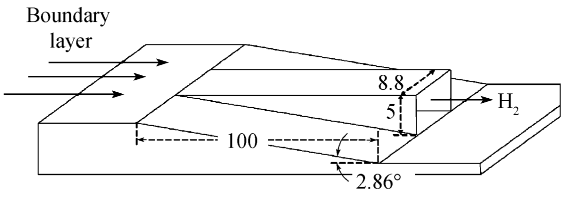


Figure 9 Expansion ramp injector [17].

realistic situations by numerical simulation. Gaseous hydrogen was injected in a two-oblique shock external compression inlet via cantilevered ramp injectors and a wall slot, as shown in Figure 10. It was found that the combustor length, determined by the shock-induced combustion process, was of the order of 25%–30% of the inlet length. Due to the incomplete mixing in the inlet, the fuel specific impulse obtained was 573 s, which was relatively low.

3.3 Detonation initiation and stabilization

At present there are two methods employed in the direct detonation initiation for propulsion systems, i.e. shock induced direct detonation initiation and non-contact ignitions such as high-energy laser [19]. The shcramjet engine employs the former one, a wedge or blunt body is placed in the supersonic flow to create an oblique shock wave that induces detonation waves. The key problem to be solved is to choose the wedge angle properly. If the angle of the wedge is too small, the corresponding oblique shock wave will be very weak, which will reduce the temperature and pressure rise across the wave, and make the detonation wave fail to initiate directly or difficult to sustain itself. On the contrary, if the wedge angle is too large, a strong overdriven oblique shock wave will be generated, which leads to a larger total pressure loss and aerodynamic resistance. Figure 11 shows the diagram of detonation wave generated by wedge.

Two problems must be solved for combustion organization in the combustor of shcramjet engine. First, the direct detonation initiation and self-sustaining must be implemented in pre-compressed high temperature mixture. Secondly, the total pressure loss must be reduced as much as possible. The later one can be realized by decreasing the angle of oblique shock wave, which, however, will reduce the pressure and temperature at the wave rear and bring disadvantages to the detonation initiation and self-sustaining. So, there must be a trade-off to solve these two problems. The combustion should be organized by CJ oblique detonation, when the total pressure loss and aerodynamic resistance can be reduced effectively [21].

Ess et al. [22] studied the heat release of detonation waves induced by blunt bodies embedded into a constant area channel flow by numerical simulation, which is shown in Figure 12. Channel blockage ratios (CBR), defined as the

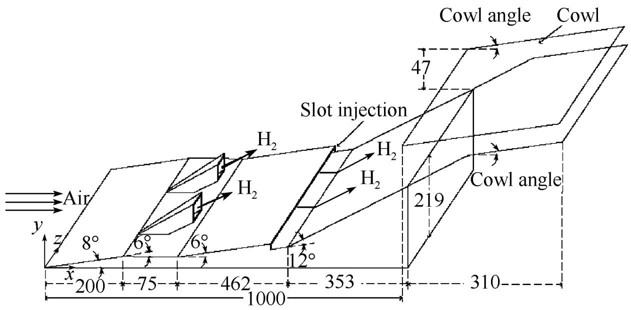


Figure 10 Baseline dual spike shcramjet inlet and combustor (unit: mm) [18].

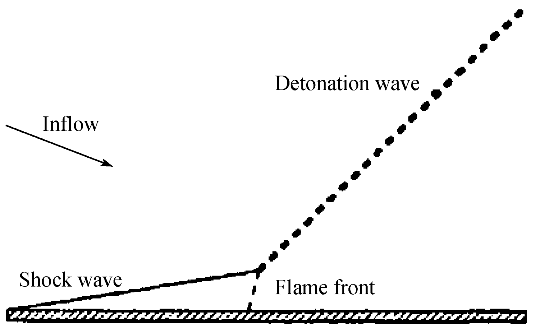


Figure 11 Wedge generated detonation wave [20].

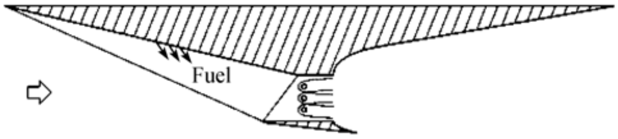


Figure 12 Scramjet with blunt-body generated combustion [22].

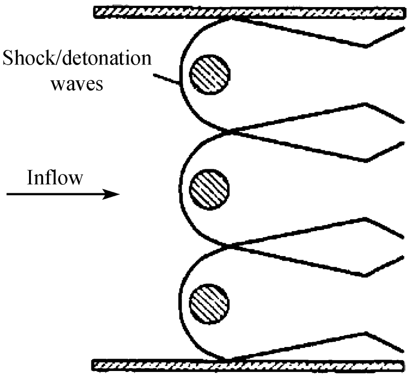


Figure 13 Blunt body generated detonation wave [20].

ratio of blunt-body diameter over channel height, in the range from 1/18 to 1/3, were examined for typical inflow conditions. For all CBRs examined detonation waves were found to be successfully initiated and sustained. The range of CBRs that produced positive thrust and the highest thrust were obtained, as well as the corresponding location where the highest thrust was achieved. The research validated the heat release and propulsion performance of shcramjet engine on the one hand, and provided gist for the design of the combustor components, inflow boundaries and nozzle on the other hand. Figure 13 shows the detonation wave generated by blunt body.

4 Ground test researches

According to published reports, only Washington University has done some ground test on shock-induced supersonic combustion accelerating vehicle so far [23,24].

The shock-induced projectile was made by titanium alloy [24], and the experiment was carried out in the 38 mm bore ram accelerator facility at the University of Washington. The projectiles were launched into reactive propellants at Mach numbers greater than 5.5 to determine if the combustion process could be shock initiated and stabilized, what levels of thrust can be generated, the reactivity of the projectile material in hypersonic flow, and to evaluate the efficacy of investigating the operating characteristics of hypersonic propulsive cycles using gun-launched projectiles. Four different projectile configurations were employed in methane- and ethane-based propellants with and without carbon dioxide diluent. Positive acceleration was observed in $CH_4/O_2/CO_2$ and C_2H_6/O_2 propellants in the range of Mach 5.5–7 for distances up to 6 m. In most cases, the acceleration process was terminated by unstart, cruise at constant velocity, or wave fall off. Sustained accelerations greater that 9000 g and average specific thrust 150 N·s/kg were achieved in these experiments. The hypersonic projectile drag coefficient in the Mach range of 5–6 was found to be C_D=0.09 from experiments in which the propellant did not ignite. Figure 14 shows the configuration of a shock-induced combustion projectile.

Figure 14 Experimental projectile [24].

5 Conclusion

As a new conceptual hypersonic propulsion system, shock-induced combustion ramjet engine will further satisfy the extreme requirements of airbreathing hypersonic vehicles to improve the integral performance. It is essential to aim at the international research front, follow the international research steps and promote its research process in our country.

1) The key techniques of shock-induced combustion ramjet engine are premixed efficiency of fuel/air, premature ignition suppressing, detonation initiation and stabilization. In order to make the engine feasible, the fuel and air must be premixed adequately at the entrance of the combustor, while premature ignition phenomenon must be prevented.

2) Shock-induced combustion ramjet engine is easy to be integrated with the airframe, which will improve the integrated design level and the flight performance of the vehicle.

3) It will make a great difference to break through the bottleneck of the scramjet engine development and promote the space and military application of hypersonic propulsion in the future by quickening the research step of shcramjet and carrying out experimental examination of ground prototypes and technique engineering as soon as possible.

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