A review on shock-induced combustion ramjet engines

Anupriya*, Bhupinder singh**

* Student at Chandīgarh University, Department of Automobile Engineering, Gharuan, Mohali(Punjab).

** Professor atChandīgarh University, Department of Automobile Engineering

Abstract

The stun instigated burning ramjet motor is the greatest air breathing propulsive framework and an appropriate alternative for high velocity flight. In this paper, hypothetical investigation and mathematical reproductions were directed to contemplate the push execution of stun initiated burning ramjet motors. First and foremost, the propulsive execution of supersonic ignition ramjet motors was hypothetically dissected by utilizing the Chapman-Jouguet explosion hypothesis. At that point, the streamlined standards of stun incited ignition ramjet motors were advanced based on the hypothetical examination results. At long last, a full-scale stun instigated burning ramjet motor was planned by the streamlined standards. Two-dimensional mathematical reproductions were led to mimic its ignition flow field and propulsive execution. The mathematical outcomes exhibit the accuracy and use of the hypothetical streamlined standards.

Keywords:

Scramjet engines, Shock-inducedcombustion, ramjetengines ,Supersoniccombustion.

Introduction

The supersonic combustion ramjet (scramjet) engine has been expected to be one of the most promising propulsion systems for hypersonic air-breathing vehicles [1,2]. Scramjets have the poten-tial to reduce the costs of accessing to space by taking air from atmosphere as an oxidizer. However, although many countries have investigated scramjets during the past 60 years, there is still a long way to go [3–10]. There are many complex theoretical and technical issues that still need to be explored and overcome to make scramjets operable for hypersonic flight. The thrust and su-personic combustion oscillation are two crucial aerodynamic issues that need for further study [3].

The first aerodynamic issue is that scramjets do not have enough thrust [3,4]. We do not know theoretically the method to increase its thrust effectively and the crucial parameters influenc-ing the thrust. For example, the studies on scramjets at the French Aerospace Lab (ONERA) were stopped at 1972 due to the difficulty of the propulsive balance of an air-breathing hypersonic vehicle. For this reason, they made the decision to concentrate efforts on rocket engines. Although the activities of scramjets at ONERA were renewed in 1992, propulsive balance still remains to be a key issue for the development of air-breathing hypersonic vehicles [7].

The second issue is the supersonic combustion oscillation, which can cause the engine unstart. Researchers usually think that the engine unstart is mainly caused by shock-induced boundary layer separation in the combustor. But Laurence et al.

[9]and Oh et al. observed the shock waves propagating upstream in the isolator in the experiments and numerical simulations, respectively. Laurence et al. observed experimentally the shock wave propagatingupstream with an absolute velocity of about 1900m/s, which is very close to the Chapman-Jouguet (C-J) detonation velocity of H2/Air mixture. In this case, the turbulence, diffusion, viscous, and heat conduction processes in ODEs are less important than that of scramjets. Their experimental results demonstrate that the engine

unstart is caused by flow choking instead of the boundary layer separation [10]. The sonic combustion in the combustor of scramjet engines determines the upper limits of the equivalence ratio and thrust.
To the best knowledge of the authors, the theoretical analysis on propulsive performance of scramjet engines is difficult and rare in publications. The theory of one-dimensional heat-addition flow was first proposed by Tsienin 1949 in order to study the propulsive performance of scramjet engines. This is the only theory that can be used to estimate the performance of scramjet engines up to now . However, this theory is based on a steady-state reactive flow field and cannot predict the unsteady phenomena in the combustor of scramjets. If the heat release in the combustor is violent, the pressure rise caused by combustion will produce shock waves in the confined space[8]. The shock-shock interaction will enhance the strength of the leading shock wave . The shock train propagates upstream to the inlet of aircraft. Therefore, this theory of steady combustion flow field cannot predict the shock waves in the isolator.

In the present study, the propulsive performance of scramjet engines is theoretically analyzed for the first time by the using C-J detonation theory. It is known that the C-J detonation is the strongest detonation wave produced by combustion. Therefore, the upper limit, critical characteristics, and propulsive performance of scramjets can be obtained . Secondly, the aerodynamic design principles of shock-induced combustion ramjet (scramjet) engines are put forth based on the theoretical analysis results. The shock-induced combustion ramjet engine has its advantages compared with the scramjet engine in high Mach number flight regimes. Finally, a full-scale scramjet engine is designed according to these principles. Two-dimensional numerical simulations are conducted to simulate its propulsive performance. The numerical simulation is not only the application but also a demonstration of the theoreticalanalysis results.

Theoretical analysis of propulsive performance

Theoretical model of C-J detonation engine

The schematic of scramjets is shown in the upper half of Fig.1. It consists of six main parts: the fore body, internal inlet, isolator, combustor, internal nozzle, and aft body. The supersonic combustion in the combustor produces pressure rise related to combustion in the confined space. The pressure rise in the combustor produces a series of shock waves, which oscillates in the isolator. The shock-shock interaction enhances the strength of the leading shock wave . If the velocity of the leading shock wave is faster than the incoming flow, it will move upstream out of the inlet. Thus, the unstart of scramjets occurs.
In order to study the characteristics of the shock waves and the propulsive performance of scramjets, we put forth a one-dimensional physical model, as is shown in the lower half of Fig.1. The flow field of scramjets can be simplified as two shock waves and one flame front. The flow direction is from left to right. The primary shock wave SW corresponds to the shock wave at the in-let. It can be an oblique shock wave or a normal shock wave. The secondary shock wave SW' represents the shock waves in the isolator. The flame front is considered to be the supersonic combustion flame in the combustor. Therefore, this simplified model can analyze the key mechanisms of scramjets[9]. However, how to analyze the strength of the shock wave SW' quantitatively is a very difficult problem up to date. In this study, the classical C-J detonation theory is used to analyze the shock wave SW'. The shock wave SW' can be considered as a C-J detonation under thermal choking conditions, which is one of the critical conditions of the scramjets.

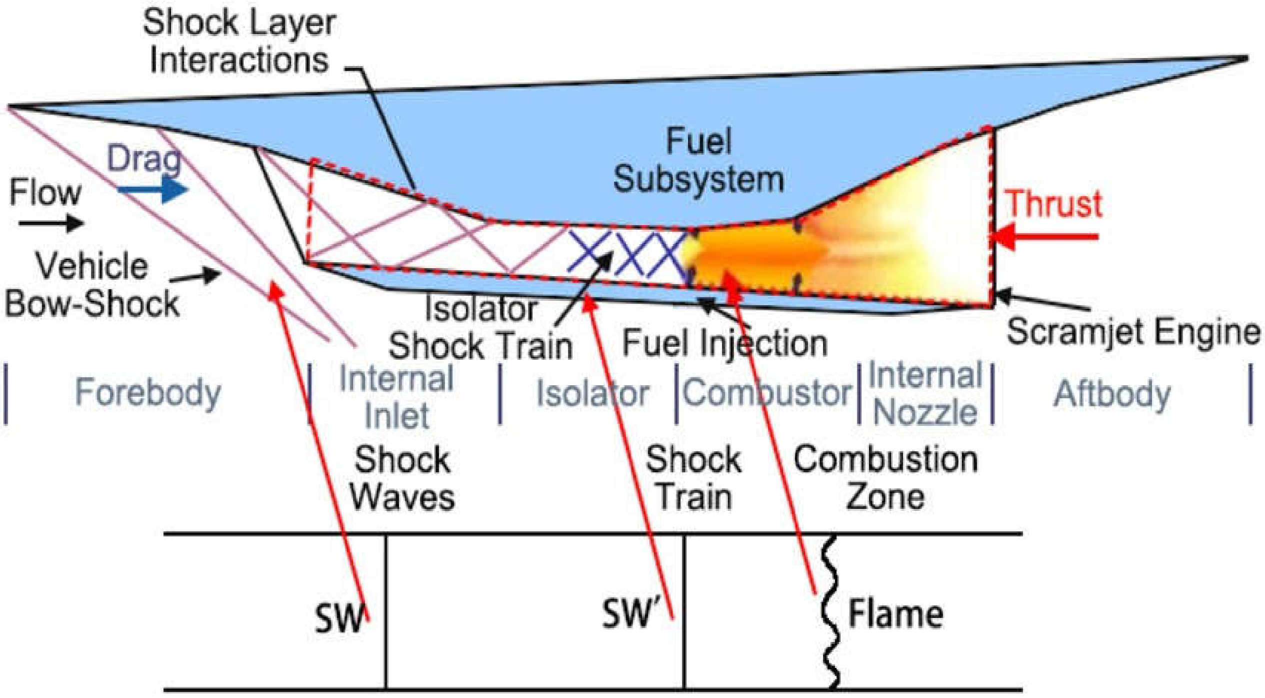

Shock Layer Interactions
Fuel Subsystem
Drag
Flow
Thrust
Vehicle Bow-Shock
Isolator Shock Train
Fuel Injection
Scramjet Engine
Forebody
Internal Inlet
Isolator
Combustor
Internal Nozzle
Aftbody
Shock Waves
Shock Train
Combustion Zone
SW
SW'
Flame

Fig.1

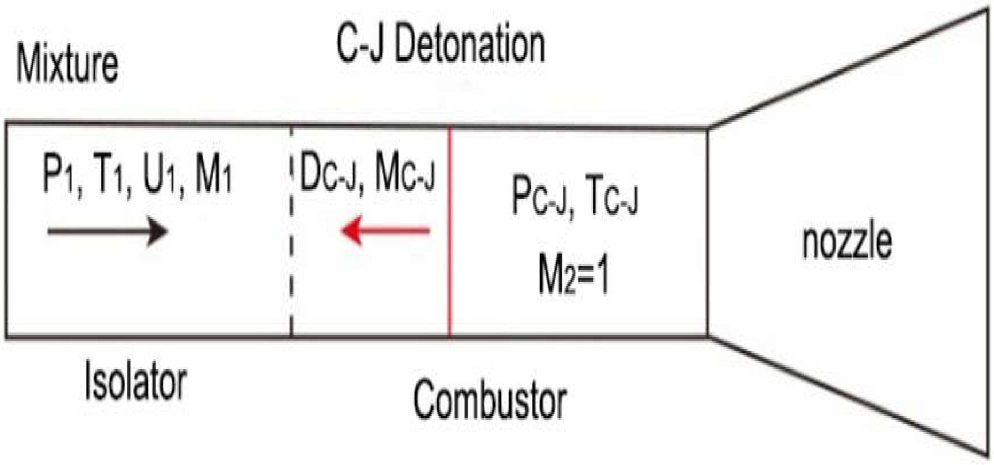

Mixture
C-J Detonation
P1, T1, U1, M1
DC-J, MC-J
PC-J, TC-J
M2=1
nozzle
Isolator
Combustor

Fig.2

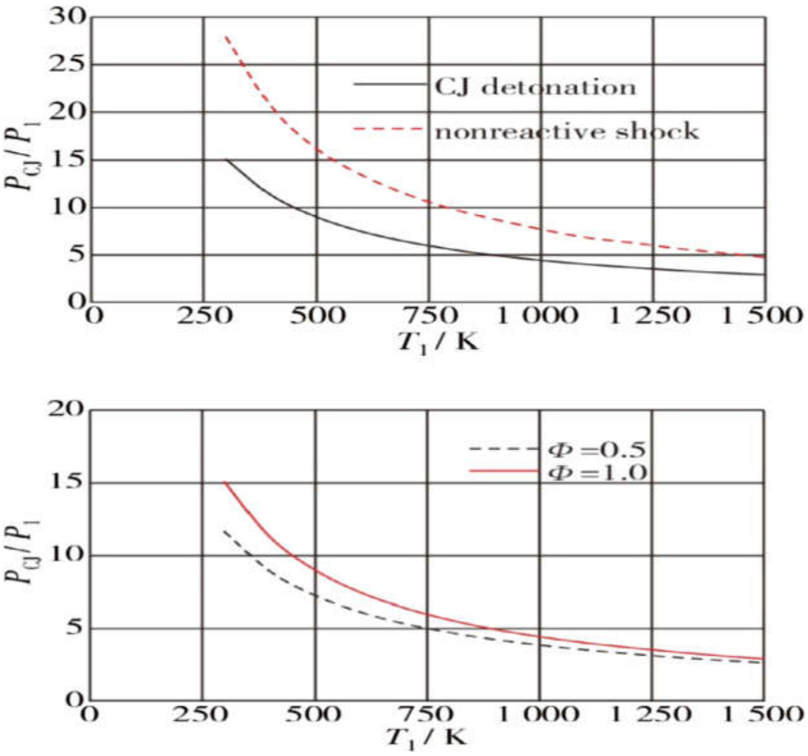

30
25
20
15
10
5
0
P_{CJ}/P_1
CJ detonation
nonreactive shock
0
250
500
750
1 000
1 250
1 500
T_1 / K
20
15
10
5
0
P_{CJ}/P_1
Φ =0.5
Φ =1.0
0
250
500
750
1 000
1 250
1 500
T_1 / K

Table 1

In this study, only the heat addition of scramjets is analyzed, while the geometry variation and boundary layer separation are not considered. The reason is that the combustion in the combustor of scramjets can be considered as constant-volume combustion and C-J detonation theory can be applied to predict the flow field quantitatively. As a result, the supersonic combustion flow field of scramjets can be controlled according to the theoretical analysis. However, there is no theory to quantitatively predict the influence of the geometry variation and boundary layer separation. There-fore, we cannot control them and have to eliminate and avoid them in operations.

The C-J detonation engine can operate steadily when the detonation velocity equals to the velocity of incoming flow in the isolator (*D*C-J=*U*1). If the detonation velocity is faster than the in-coming flow, it will propagate upstream out of the inlet of aircraft and cause the engine unstart. Otherwise, the flame will be blown out. The gas in the C-J detonation engine is combustible mixture. But the gas in the isolator of scramjets is air. It will mix with fuel and become premixed combustible mixture at the entrance of the combustor. The mixing process of the fuel and air in the isolator is ignored in the C-J detonation engine. For scramjets, the formation of C-J detonation in the combustor will decay in the isolator. However, in reality, the length of the isolator is so short that this process can be ignored.

The C-J detonation is the strongest combustion wave caused only by combustion. The Mach number of detonation products relative to the detonation front is unity. This means that the C-J detonation is a thermal choking flow. Therefore, the pressure of detonation products is the most important parameter for thrust of scramjet engines. And the C-J detonation velocity is the most important parameter for the steadiness of the supersonic flow field. In the following part, the crucial parameters influencing the C-J detonation pressure and velocity are studied theoretically and the aerodynamic design principles of shock-induced combustion ram-jet engines are deduced according to the analytical results.

Theoretical results

In the theoretical analysis, the combustible mixture is chosen to be H2/air mixture with different equivalent ratio (φ). The H2/air mixture is usually used in flight experiments such as X-43A and HyShot II. Hydrogen is the most favorable fuel for scramjets be-cause its ignition delay time is very short. The short ignition delay time is very important for oblique detonation initiation. The static pressure of mixture in the isolator is assumed to be 101,325Pa (1atm). The static temperature in the isolator is varied from 300K to 1500K to simulate different compression conditions of the inlet. The parameters of stoichiometric H2/air C-J detonation under different initial temperature are calculated by using classical C-J detonation theory The parameters include C-J detonation The parameters include C-J detonation

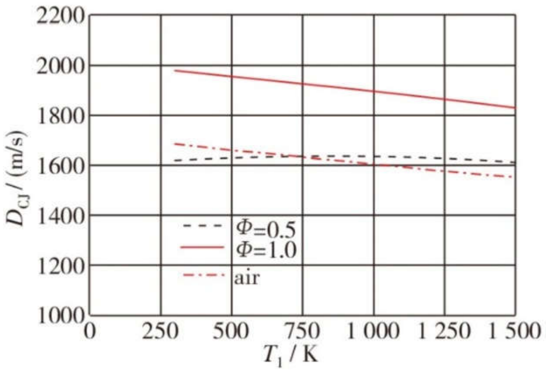


Fig.3 Detonation velocity of stoichiometric H_2 /air C-J detonation under different initial temperature and different equivalence ratio.

Mach number *M*C-J, C-J detonation velocity *D*C-J, and pressure ra-tio*P*C-J/*P*1.
The combustion pressure is a crucial parameter to predict the propulsive performance of scramjets. The pressure ratio *P*C-J/*P*1of C-J detonation at different initial static temperature and different equivalent ratio are plotted in Fig.3. From Fig.3a, it can be found that the pressure ratio *P*C-J/*P*1of C-J detonation decreases expo-nentially with the increase of the initial static temperature. The pressure ratio is very sensitive to the initial static temperature. The main reason is that C-J detonation can be considered as constant-volume combustion. The pressure ratio is *P*C-J/*P*1=15.08at initial static temperature of 300K; the pressure ratio is *P*C-J/*P*1=4.46at 1000K; and the pressure ratio is only *P*C-J/*P*1=2.93at 1500K. This is the upper limit of pressure ratio obtained by supersonic combustion. This means that the propulsive performance of scram-jet engines becomes worse with the increase of the air temperature at the entrance of the combustor Therefore, in order to achieve a better performance, the intake flow static temperature in the isolator should be kept lower.

Theshockwavevelocityisacrucialparametertopredictthe steadinessofthecombustionflowfieldofscramjets.Fig.3shows thedetonationvelocityatdifferentinitialtemperatureandequivalenceratio.TheshockwavevelocityofairwiththesameMach numberasC-Jdetonationisalsoplottedinthisfigure.FromFig.3 wecanfindthatthedetonationvelocitydecreasesslowlyasthe initialtemperatureincreases.Thedetonationvelocityis1979m/s atinitialtemperatureof300Kand1830m/sat1500K,respectively.Thisresultshowsthatthedetonationvelocityisinsensitive totheinitialtemperature.Thevelocityofshockwaveintheair withthesameMachnumberisabout300m/sslowerthanthatof C-Jdetonation.Thereasonisthatthesoundspeedofairislower than that of the H_2/airmixture.

These results indicate that if the detonation wave propagates upstreamintotheairintheisolator,itwillpropagaterapidlyto theinletofscramjetsandcausetheengineunstartbecauseits velocityisabout300m/sfasterthanthevelocityoftheincomingflow.Supposethelengthoftheisolatoris1m,ittakesabout
3.3msfortheshock wave totraveltotheinletandtheoscillationfrequencyisabout300Hz.

Numerical simulation of shock-induced combustion ramjet engines

Geometry of shock-inducedcombustion ramjet engines

The shock-induced combustion ramjet (scramjet) engines or oblique detonation engines (ODEs) are more potential for hyper- sonicflight(Machnumberabovenine)becausethetotalenthalpy ofthehypersonicflowishighenoughtoinitiatetheobliquedetonation.Thekeycombustionmechanismistheauto-ignitionof

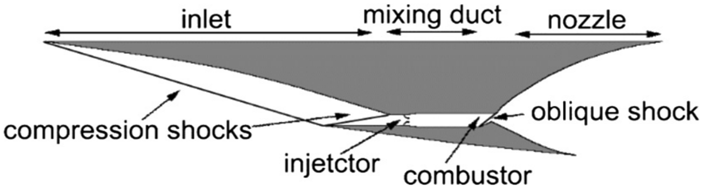


Fig.4 The schematic of shock-induced combustion ramjet engines

thereactantsheatedbyobliqueshockwaves.Inthiscase,theturbulence,diffusion,viscous,andheatconductionprocessesinODEs arelessimportantthanthatofscramjets.Thisisthemaindifference between scramjets andscramjets.

Fig.4 showstheschematicofScramjets.Itconsistsoffour parts:theinlet,themixingduct,thecombustorandthrustnozzle. The hydrogen fuel is injected at the entrance of the mixing duct and mixes with the supersonic airflow compressed by the in-let. In the combustor, a wedge generates an oblique shock wave, which ignites the combustible gases and induces an oblique detonation wave. This combustion process is also called shock-induced combustion.

Results and discussion

The pressure contours of the full-scale scramjets at φ=0.57are shown in Fig.10. Fig.10b clearly shows the shock trains caused by injectors and expanded mixing duct. The steady flow field at φ=0.57is obtained. The incoming flow comes into the mixing duct through two oblique shock waves. Positions of the compression shock waves are close to the inviscid design. The theoretical values have a pressure of 11,456Pa, a temperature of 976K and a velocity of 2576m/s. The Mach number of theoretical values is 4.11. The boundary layer spills out from the boundary bleed channel and this measure can effectively eliminate the influence of shock wave-boundary layer interaction. It ensures that the main- stream in the mixing duct has uniform velocity and temperature. Thex-velocitycomponentatthemixingductentranceisfaster than the C-J detonation velocity of stoichiometric H_2/air mixture whichis1950m/s.Accordingtotheaboveprinciples,theoblique shockwavestandsinfrontofthewedgeandtheflowfieldkeeps steady.

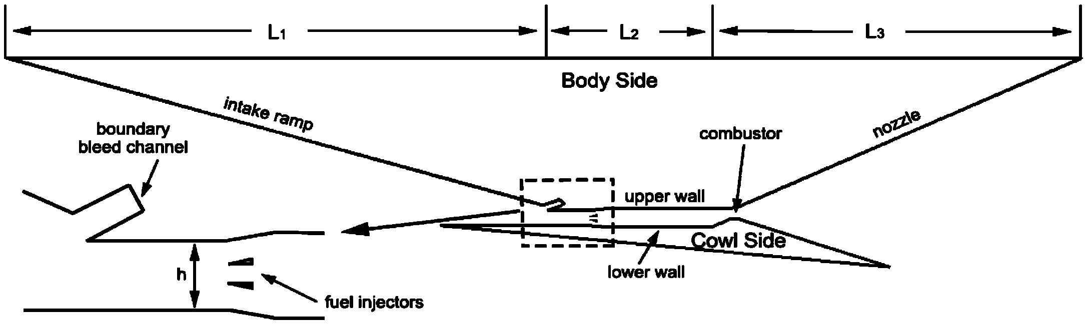
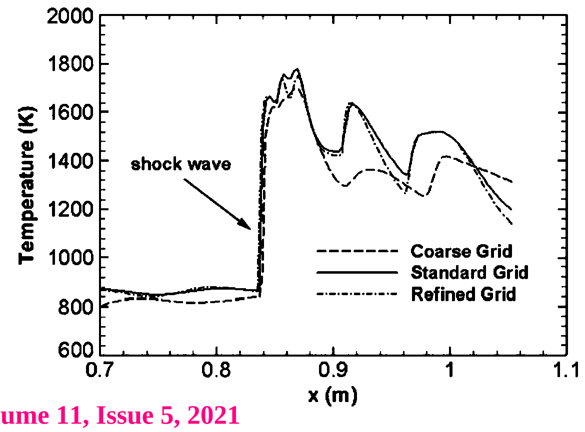


Fig.5 The configuration and details of the simplified shock-induced combustion ramjet engine designed according to the principles.



ThedetailedflowfieldofthecombustorisshowninFig.6 .itcanbefoundthatshock-inducedboundarylayer separatesattheupperwallofthecombustorandasmallseparationbubbleisproduced.Anewobliqueshockwaveappearsin frontoftheseparationbubbleandleadstoashock-shockinteraction.However,thewholeflowfielddoesnotbeinfluencedbythe boundarylayerseparationbecauseofthedivergentnozzle,which expandsthecombustionproductstolowerpressure.

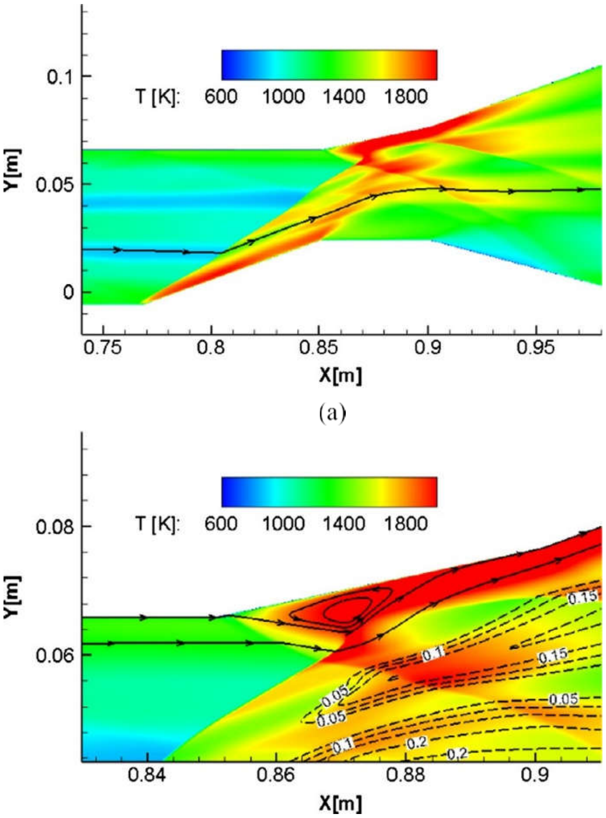


Fig. 6 The temperature contours (a) and local enlarged contours (b) in the combuster with φ 0.57; streamlines: solid lines; mass fraction of H_2 O: numbers and dashed isoclines.

Meanwhile,thecurvesofthecumulativepressureandfrictional forces(excludetheboundarybleedingchannel)inthex-direction oftheinternalwalls(includetheuppersideandlowerside)are presentedinThecumulativeforcesaredefinedasanintegralofthelocalsurfacepressureandthelocalwallangle,where thelengthinthez-directionissettobe1.0m.Theresultsindicate thatthecombustion-inducingwedgegenerates52.0%ofpressure drag,6.0%offrictiondragand39. 5%oftotaldragalthoughits lengthisonly2.15%oftotallength.Theshock-inducedcombustion finallygeneratesanetthrustof791Nduringthewholeprocess.Thesearetheprimaryresultsofthissimplifiedconfiguration.The configuration and thrust performance need further optimizationbecausethemainpurposeofthispaperistostudythecombustion flow fields of scramjets andScramjets.

Conclusions

In this paper, the C-J explosion hypothesis is firstly used to investigate the flow field of scramjets. This hypothesis can foresee the pressing factor in the combustor of scramjets and the stun wave engendering up-stream in the isolator when the burning flow field is warm stifling. Some helpful and general ends are gotten by the hypothetical investigation. Based on hypothetical examination, streamlined plan standards for scramjets and stun prompted burning ramjet motors are advanced. A full-scale stun incited ignition ramjet motor is planned by these standards. Two-dimensional mathematical reproductions are directed to consider the flow field of this motor at M9, 40 km elevation and equality proportionof solidarity. Consistent flow field is acquired which show the rightness of the streamlined plan standards.

References

[1]. A. Ferri, Review of problems in application of supersonic combustion, Aeronaut. J. 68(645) (1964) 575–597.

[2]A.Ferri, Review of scramjet propulsion technology, J. Aircr. 5(1) (1968) 3–10.

[3]E.T. Curran, Scramjet engines: the first forty years, J. Propuls. Power 17(6) (2001) 1138–1148
.

[4]J.W. Kim, O.J. Kwon, Modeling of incomplete combustion in a scramjet engine, Aerosp. Sci. Technol. 78 (2018) 397–402.

[5]Z. Ren, B. Wang, B. Hu, et al., Numerical analysis of supersonic flows over an Aft-ramped open-mode cavity, Aerosp. Sci. Technol. 78 (2018) 427–437
.

[6]J. Shin, H.G. Sung, Combustion characteristics of hydrogen and cracked Kerosene in a DLR scramjet combustor using hybrid RANS/LES method, Aerosp. Sci. Technol. 80 (2018) 433–444

7]D. Scherrer, O. Dessornes, M. Ferrier, et al., Research on supersonic combustion and scramjet combustors at ONERA, J. Aerosp. Lab. 11 (2016) 1–19.

[8]H.D. Shen, Y.B. Liu, B.Y. Chen, Control-relevant modeling and performance lim-itation analysis for flexible air-breathing hypersonic vehicles, Aerosp. Sci. Tech-nol. 76 (2018) 340–349.

[9]R.J. Clark, S.B. Shrestha, A review of numerical simulation and modeling of combustion in scramjets, proceedings of the institution of mechanical engi-neers, part G, J. Aerosp. Eng. 229(5) (2015) 958–980.

[10]T.Mitani, K. Tani, H. Miyajima, Flow choking by drag and combustion in super-sonic engine testing, J. Propuls. Power 23(6) (2007) 1177–1184.