Recent Developments in Flame-Holding Mechanisms in Supersonic Combustion Process of Hypersonic Air-Breathing Vehicles

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About me

- I am an undergraduate mechanical engineering student at Vellore Institute of Technology, Vellore, India.
- My research interests lie in Hypersonic and Supersonic Flows, Scramjets, Early Descent Landing (EDL) & Supersonic Retro-Propulsion and Hybrid-Propellant Rocket Motor development.
- I also work as a propulsion engineer at Team Sammard, where we are developing a Hybrid Propellant supersonic rocket. The rocket is going to be launched at Spaceport America Cup’21.

Scramjet (Supersonic Combustion Ramjet)

- A scramjet (supersonic-combustion ramjet) is a ramjet engine in which the airflow through the engine remains supersonic, or greater than the speed of sound. Scramjet powered vehicles are envisioned to operate at speeds up to at least Mach 15.

SUPERSONIC COMBUSTION PHYSICS AND COMPUTATION

- With the broad range of flying conditions in the hypersonic regime, the processes in the supersonic combustion chamber are subject to large variations in thermodynamic conditions.
- At the low range of the hypersonic flight regime, the heat deposition in the combustion chamber is relatively large compared with the incoming flow energy; hence the heat deposition substantially reduces the air speed and a large pressure rise is experienced with possible flow separations.
- At the higher range of the hypersonic regime, close to Mach 25, which is considered the upper envelope of air-breathing propulsion, the heat addition may amount to only 10% of the incoming airflow enthalpy. The heat-release effects are less pronounced. [1]

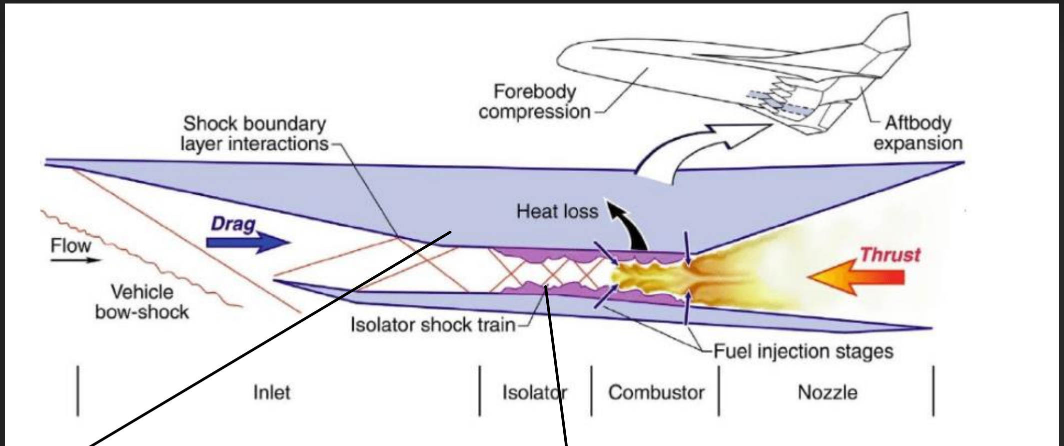
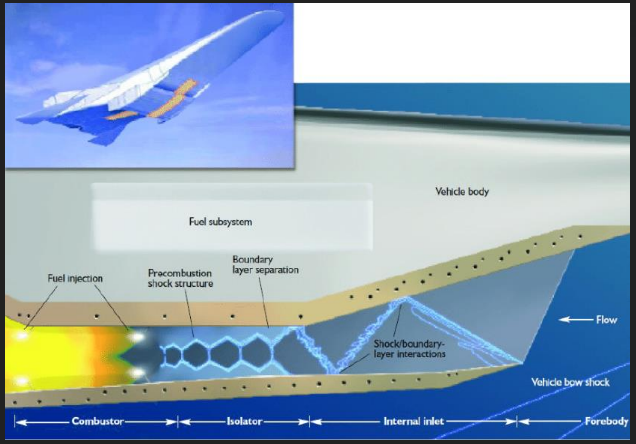
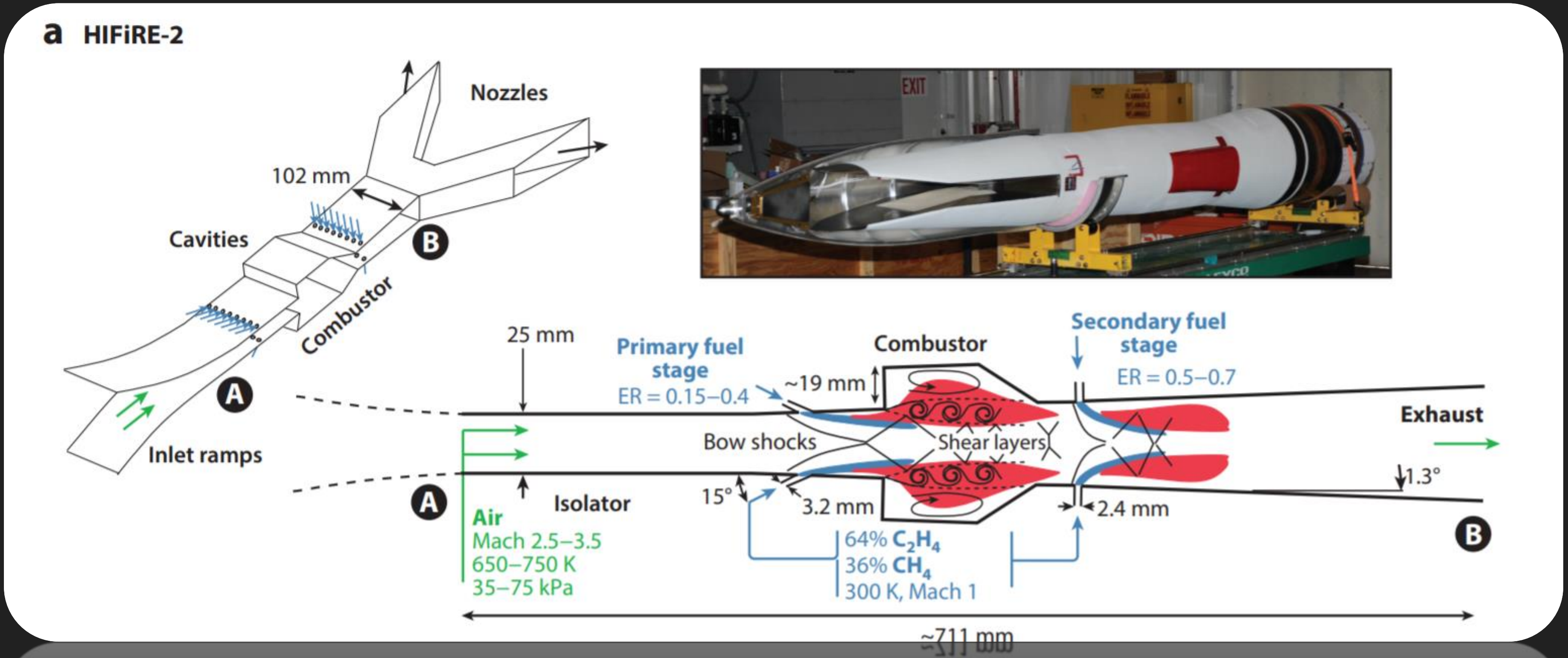


Figure 1 Schematic of a scramjet [6]

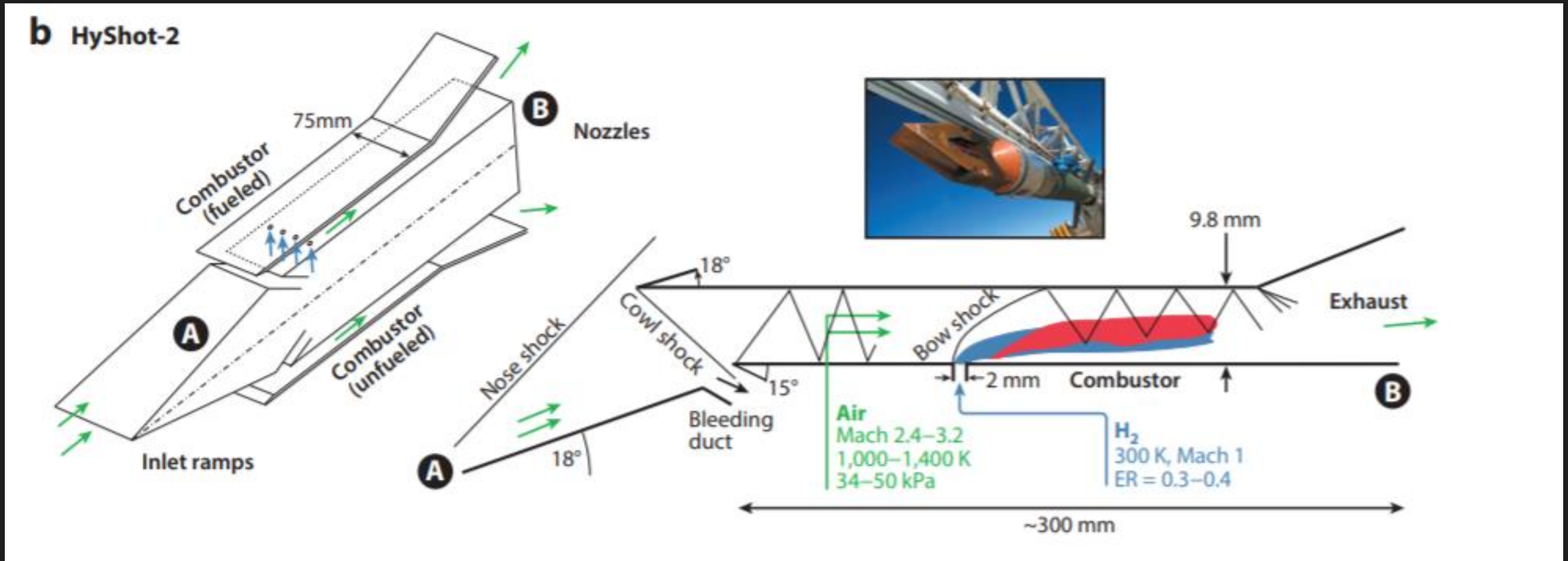


Some Popular Scramjet Combustor Designs[2]



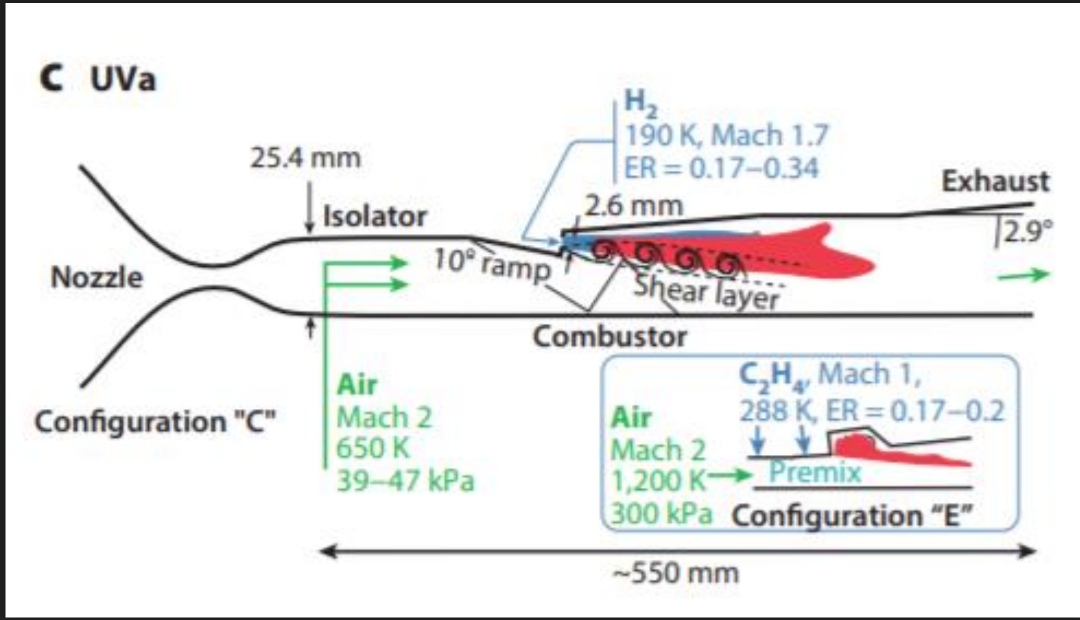
- Hydrocarbon-fuelled
- Mach 8

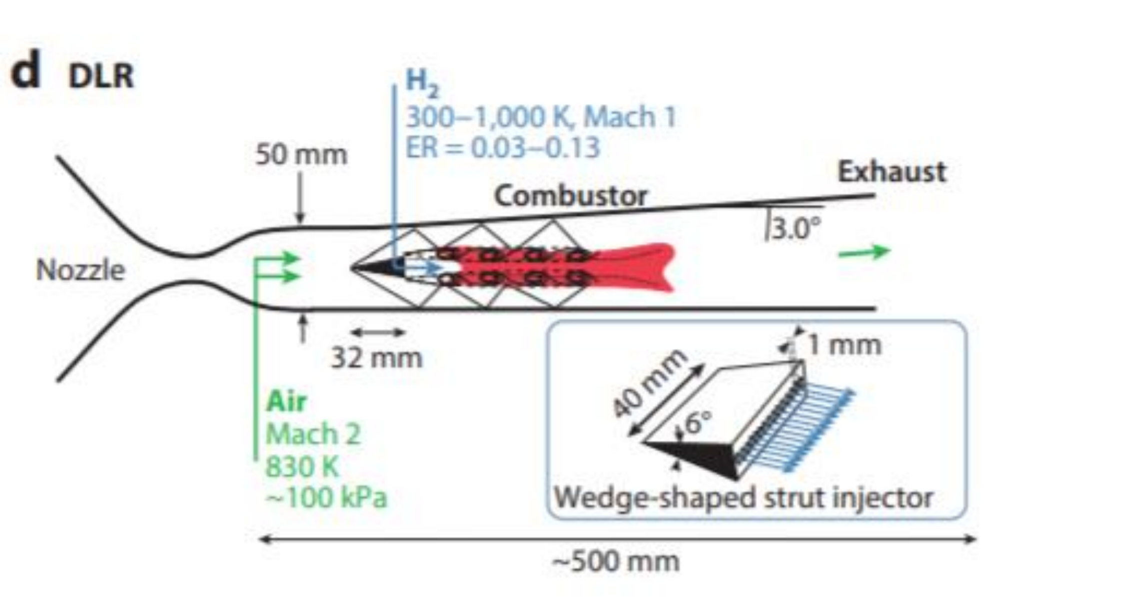
Some Popular Scramjet Combustor Designs



- Hydrogen-fuelled
- Mach 7.6

Some Popular Scramjet Combustor Designs





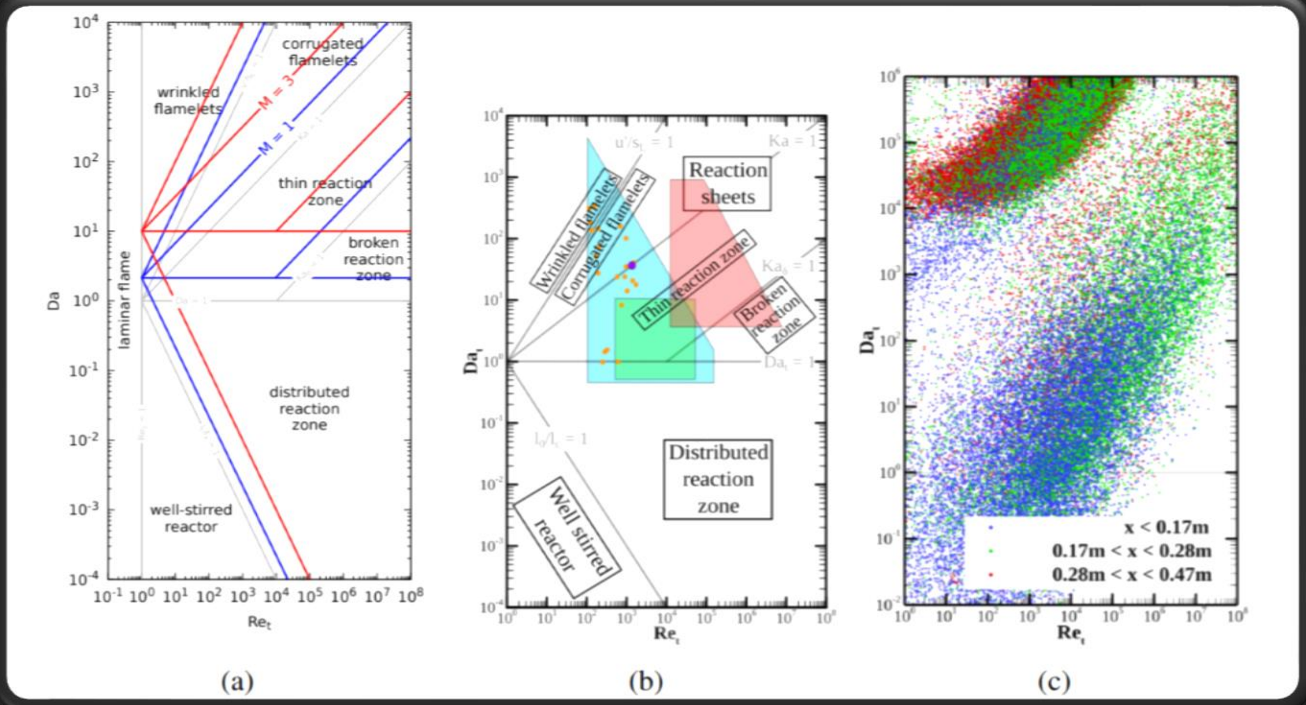
Parameters defining Turbulent Combustion

- Damköhler Number (Da): It is the most important parameter in defining the turbulent combustion regimes. Dthe ratio of Turbulent time scale $\tau_t$to chemical time scale τ_c , can be used in both the premixed an non-premixed conditions.

$$Da = \frac{\tau_t}{\tau_c}$$

- Turbulent Reynolds number: The ratio of product of eddy turnover viscosity and its size to the product of flame speed and its thickness is defined as the Turbulent Reynolds Number (Re_t). Like Damköhler Number, it too, can be in both premixed and non-premixed conditions.
- Karlovitz Number: Karlovitz number, is used to further refine the turbulent combustion regime. It is defined as the ratio chemical time scale(τ_c)to the Kolmogorov time scales. Based on flame thickness(l_f)and reaction zone thickness(l_R), the Karlovitz number can be defined in two ways- based on flame thickness and thickness of reaction zone.

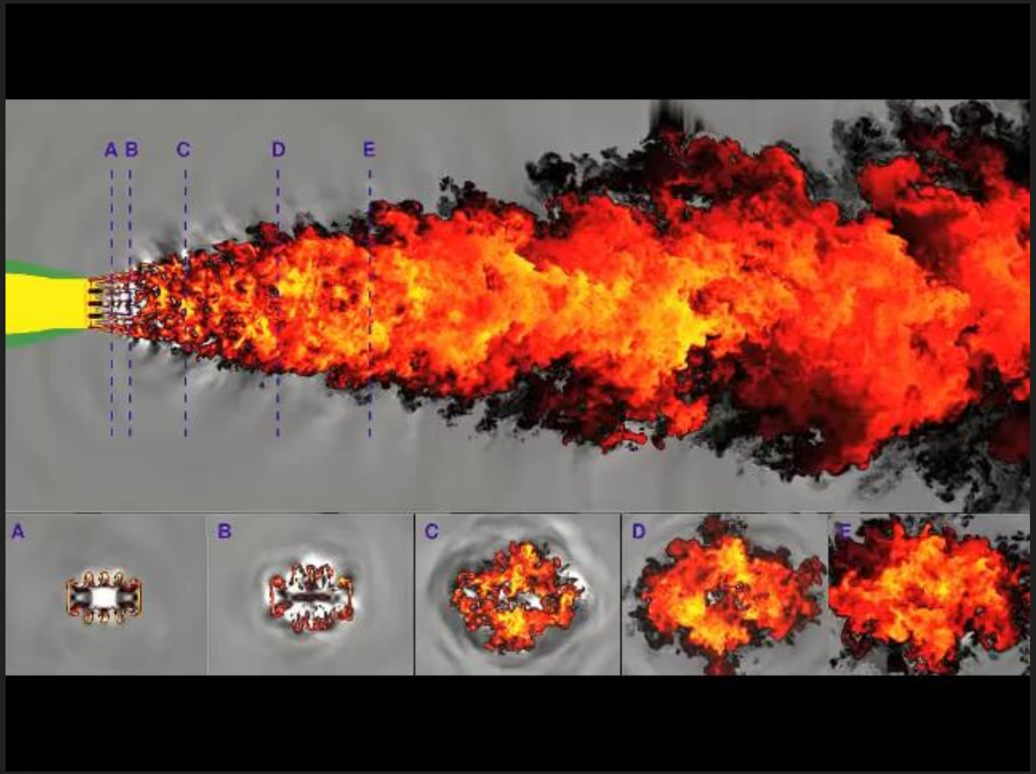
Parameters defining Turbulent Combustion



(a) Change in the boundary of combustion regimes with Mach number, adapted from
(b) Results of supersonic turbulent combustion.
(c) Large-Eddy Simulations (LES) of combustion regimes in a scramjet engine [3]

Physical Characteristics of Supersonic Combustion [2]

- The fuel and oxidizer flow separately into the combustor.
- The characteristic velocities involved in the fuel and oxidizer free streams are two to three orders of magnitude larger than typical premixed flame propagation speeds.
- Close to the injector the both the time scales, chemical time scale and molecular diffusion time scale, become almost equal (Da=1). This results in chemically frozen region that is characterized by mixing without reaction and is followed by a ignition front.
- In the remaining region the Da→∞, as the chemical time scale becomes very small compared to molecular diffusion time scale.



Conservative Equations for Supersonic Combustion

In supersonic combustion calculations, the flow field is described by the Navier–Stokes and species conservation equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla P + \nabla \cdot \boldsymbol{\tau},$$

$$\frac{\partial \rho e_t}{\partial t} + \nabla \cdot (\rho \mathbf{u} e_t) = -\nabla \cdot (P\mathbf{u}) + \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u}) - \nabla \cdot \mathbf{q},$$

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho \mathbf{u} Y_i) = -\nabla \cdot (\rho \mathbf{V}_i Y_i) + \dot{w}_i, \quad i = 1, \ldots N,$$

Fuel Selection

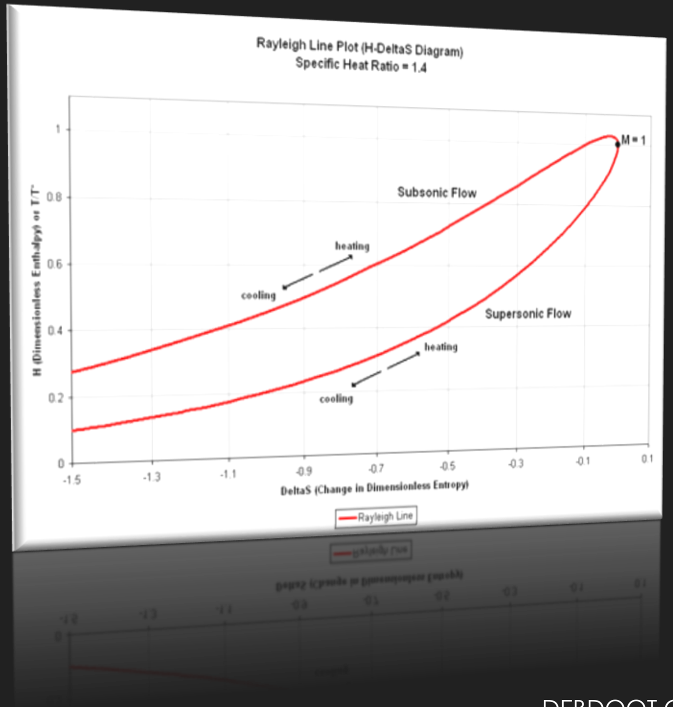
- H_2 - Gaseous andLiquid form; High diffusivity, lower ignition energy, wide flammability limits (4-75%), high calorific value (120 MJ/Kg); low density (71kg/m^3);
- C_2H_4 - Gaseous; wide flammability limits (2.7-36%), high density (40.6kg/m^3); lower calorific value (45Mj/Kg)
- ***Kerosene***- Liquid; higher density (804kg/m^3); lower calorific value (45 MJ/kg), narrow flammability limit (0.6-4.9);
- ***Effervescent kerosene***.

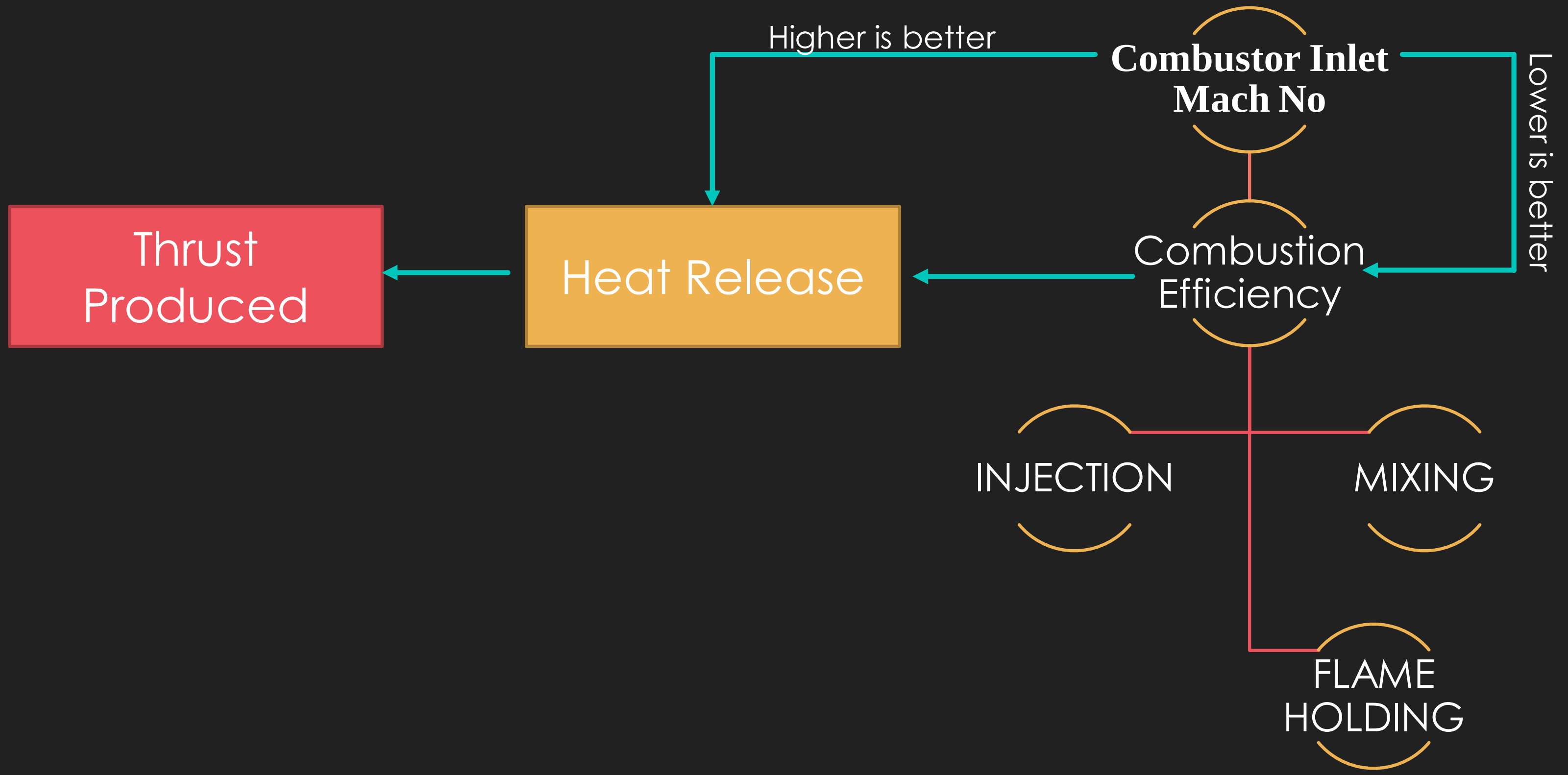
Supersonic Combustor Design

Introduction:

- The basic aim of scramjet combustor is to generate thrust. This is done by increasing the specific enthalpy of the flow and converting it into useful kinetic energy. Thus, the amount of generated thrust is largely dependent upon the heat released that takes place inside the combustor.
- According to the supersonic branch of the *Rayleigh curve*, the heat release is dependent on the Mach number at which the flow enters inside the combustor.
- At a specific Mach no. a certain amount of heat can be added until it thermally chokes. Or in other words, higher the incoming Mach No. to the combustor greater the amount of heat can be added to the flow before it thermally chokes. Therefore, the amount of heat release is dependent on the combustor itself and the incoming Mach no.

Fundamental Issues in Supersonic Combustion





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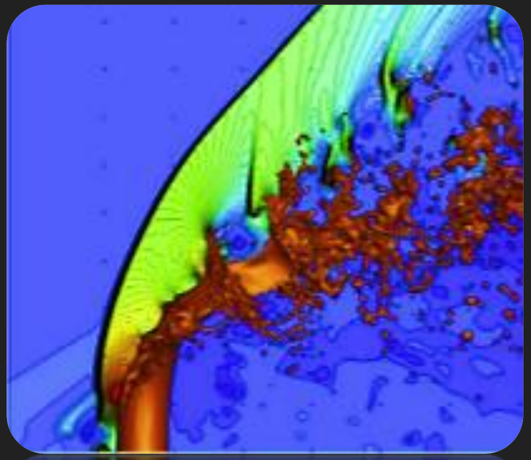
Supersonic Combustor Design: The Injection Process

1. Injectors:

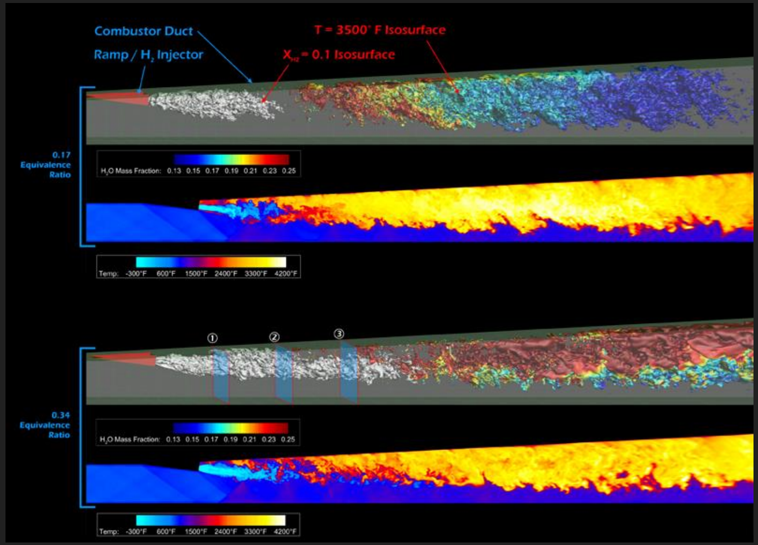
- The most challenging objective in fuel injection in a supersonic combustor is to distribute the fuel span-wise direction and vertical direction, such that, it spread across the whole correctional area of the combustor uniformly.
- The strategy of fuel injection, which determines the droplet size, becomes crucial for good mixing and high combustion efficiency. Smaller the size of the droplets the faster it will evaporate and burn effectively.
- However, if the droplet size is too small then they will not be able to penetrate the incoming supersonic flow and mix effectively. They will tend to sweep downstream with the flow. On the other hand, larger droplets can penetrate the flow effectively but will take a longer time to evaporate. This will result in a large fraction of fuel injected remain unburnt.
- Therefore, from the combustion perspective, the smaller droplet size is better, whereas, from mixing prospective larger droplet size is better. An optimal droplet size for a scramjet combustor of about 1 m long would be around 30 microns.



Supersonic Combustor Design: The Mixing Process

2. Mixing:

- In most scramjet combustors, the combustion process is mixing controlled rather than kinetic controlled. Hence, the mixing process becomes an important aspect to investigate.
- The eddies which from due to the shear layer between the incoming air and fuel assist the mixing process. However, in certain regions where the flow is of high Mach no. is often characterized by kinetics.
- With an increase in Mach no. the increased compressibility adversely affects the mixing and combustion processes. The growth rate of mixing layers and mixing is significantly reduced. In addition, the combustor and injector designs also play a very important role in mixing.

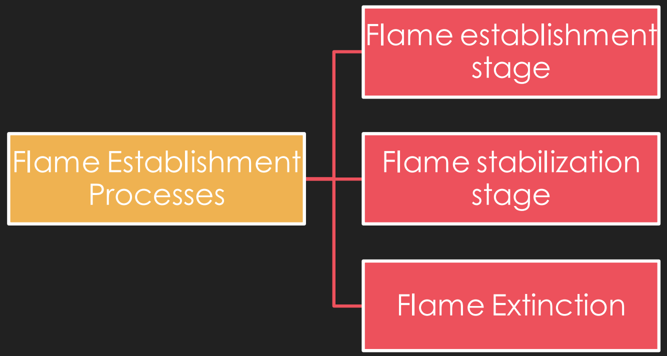


Supersonic Combustor Design

3. Flame Holding:

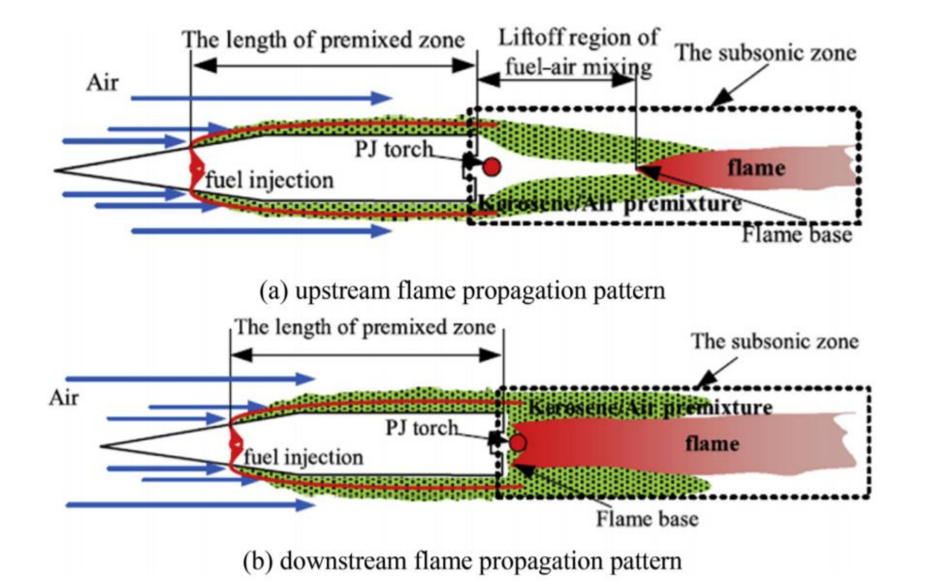
-Lighting a matchstick in a hurricane condition and sustaining the flame

- Flame holding in a supersonic combustion process is an extremely important aspect of a supersonic combustion ramjet or better known as Scramjet. After injection and mixing of fuel with the incoming supersonic flow of Mach no 2 to 2.5, a challenging task is to continue the combustion process, and here comes the role of flame holders.
- In afterburners, V-gutters are extensively used for injection and mixing of fuel with the incoming subsonic flow. But, in the case of a supersonic ramjet engine, a V-gutter based fuel injection system will be very inefficient. It will produce a strong bow-shock which will result in a substantial loss in stagnation pressure.
- There is a large body of work in this area for designing and analyzing more efficient and aerodynamic flame holders or strategy of fuel injections. *Injecting directly through the walls*, or *cavity*, *ramps*, and *struts* based fuel injection methods are the prominent methods.



Flame Propagation

- The sustained and stable supersonic combustion processes require a balance between the flame propagation velocity and the fluid speed. The flame propagation pattern varies with the increase of the equivalence ratio, and there are upstream propagation pattern and downstream propagation
- With the increase of the fuel ER, the back pressure induced by combustion suddenly propagates upstream into the isolator, leading to a large pressure rise.
- With a lower equivalence ratio, the combustion is established and stabilized downstream of the cavity.

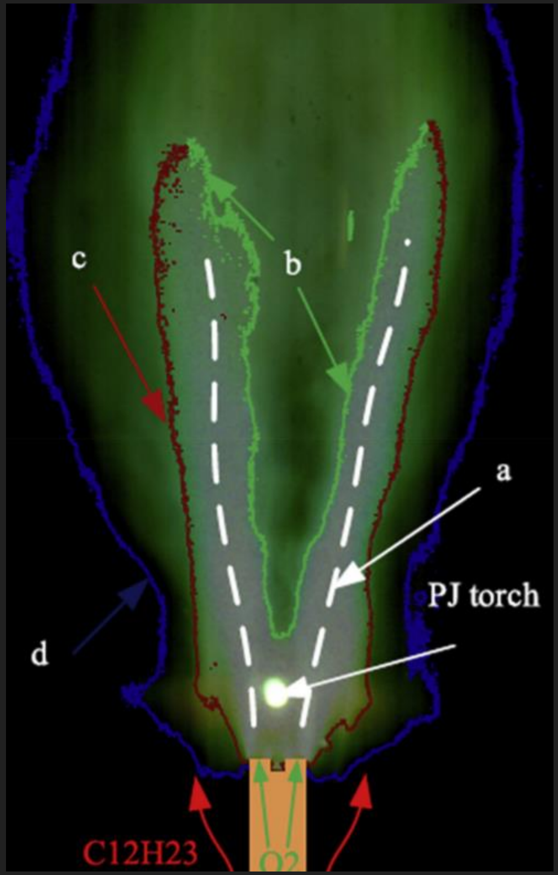


(a) upstream flame propagation pattern

(b) downstream flame propagation pattern

Flame Stabilization Mode

- The flame stabilization in the dual-mode ramjet/scramjet combustor is essentially determined by the interaction between flow dynamics and chemical reactions, and it is affected by the combustor inlet conditions .
- Generally, the global flame can be stabilized in a wide range of equivalence ratio ranging from 0.15 to 0.75 with the help of the pilot strut flame holding, and the thermal chocking is beneficial to the self-stabilization of the pilot flame
- In the flame stabilization mode, the flame can be divided into three parts, namely, the main premixed combustion zone, the oxygen-enriched diffuse combustion zone, and the fuel-enriched diffuse combustion zone.[4]



Summary of some flame stabilization investigations[4]

Information for the flame stabilization mode investigated in partial literature.

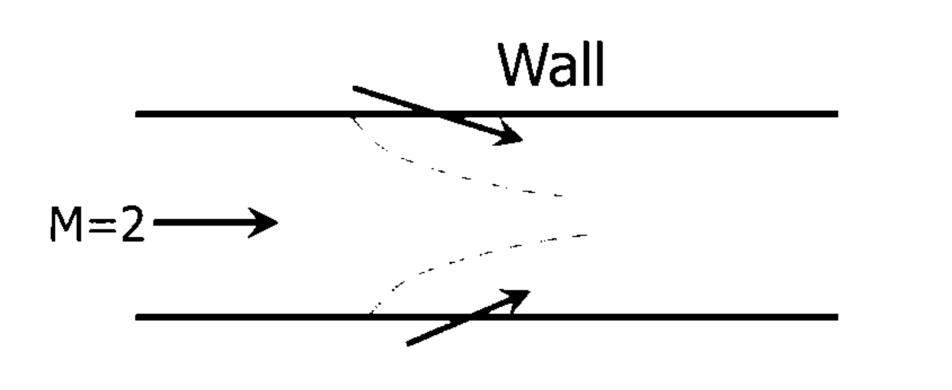
Authors	EXP/CFD	Fuel type	Mach number	Flameholder	ER	Combustion mode
Hariharan et al.	CFD	Hydrogen	2.0, 2.5, 3.0	Ramp	4.0	Supersonic combustion
Wu et al.	CFD	Hydrogen	2.0	Strut	0.034	Supersonic combustion: the induction stage, the transition stage and the intense combustion stage
Wang et al.	CFD	Hydrogen	2.52	Cavity	0.19, 0.37	Supersonic combustion: the most concentrated heat release regions are all located near the cavity rear wall
Yuan et al.	EXP	Ethylene	2.5	Cavity	0.1–0.8	Scramjet mode: the flame is stabilized in cavity shear layer Ramjet mode: the flame is stabilized in jet-wake
Tian et al.	EXP and CFD	Kerosene	2.0	Cavity	0.0, 0.6, 0.8, 0.9, 1.0, 1.1	When ER = 0.6, there are large differences in combustion performance. When ER = 0.8, there are little differences in combustion performance.
Xiao et al.	EXP and CFD	Kerosene	3.0	Cavity	0.45–0.8	Scramjet mode: the heat release is distributed equally, and there is no large separation region in isolator. Ramjet mode: the heat release is distributed concentrated, and there is large separation region and shock train in isolator.
Zhang et al.	EXP and CFD	Kerosene	2.0	Cavity and strut	Strut: 0.15–0.35 Wall: 0–0.3	Scramjet mode, weak ramjet mode and strong ramjet mode
Masumoto et al.	EXP	Hydrogen	2.5	–	0.2, 0.4	Nonignition, weak combustion, supersonic combustion, and dual-mode combustion
Yang et al.	EXP	Kerosene	2.0	Strut	0.6–1.2	Supersonic combustion, dual-mode subsonic combustion and subsonic combustion
Yan et al.	EXP	Hydrogen, ethylene	2.0	Aero-ramp	0.1–0.4	Pure scram mode, dual-mode scram mode and dual-mode ram mode
Xue et al.	EXP	Kerosene	2.3	Cavity and strut	0, 0.5, 0.68, 0.76	Weak combustion mode, rocket-scram mode, rocket-ram mode and ram mode
Huang and Yan	CFD	Hydrogen	1.7, 1.9, 2.1 and 2.5	Strut	3.43, 7.0, 10.0, 15.0[a]	Ramjet mode and scramjet mode
Tian et al.	CFD	Kerosene	2.0	Cavity	0.1 and 0.3	Supersonic combustion and subsonic combustion
Zhu et al.	EXP	Kerosene	2.0, 3.0	Strut and cavity	0.8	Lower inflow enthalpy condition: subsonic combustion mode Higher inflow enthalpy condition: supersonic combustion mode

Note: "EXP" denotes the experimental test, and "CFD" denotes the computational fluid dynamics. "ER" denotes the equivalence ratio. "a" denotes the jet-to-crossflow pressure ratio.

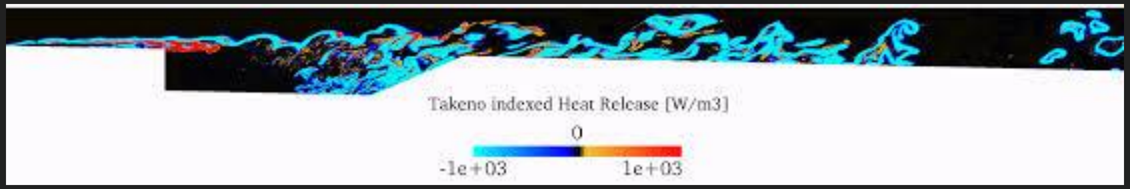
Flame holders

a. Injection through walls:

- Wall injection, is the simplest way of injecting fuel directly into the flow is through the combustor wall. But this way of injection has its own disadvantages; as the fuel is injected into a high-speed flow the fuel remains in proximity to the wall and burns there.
- As the fuel burn near the wall and due to extensive heat release combustor wall start melting. Thus, this injection through the wall is probably the poorest way to inject fuel.



Flame Holders



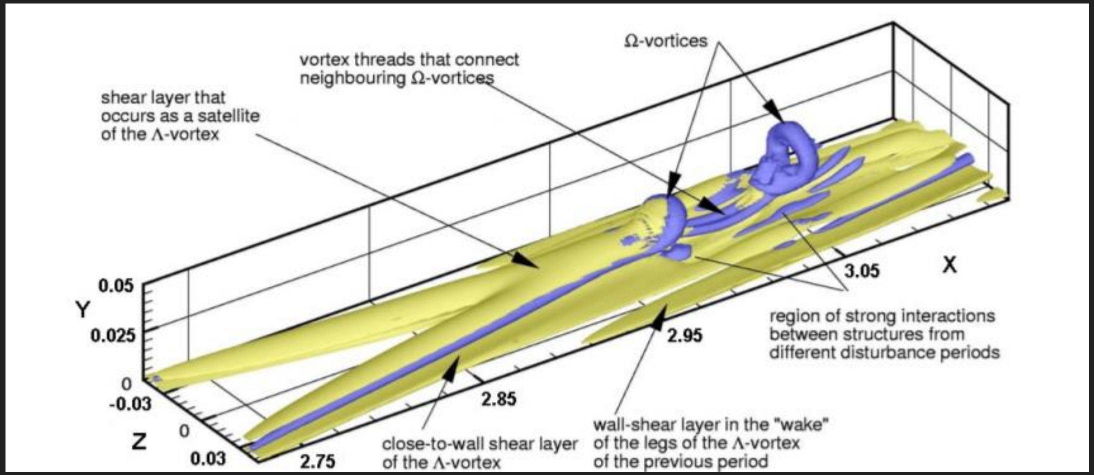
b. Cavity Based Injection Method:

- Cavities provide a great extent of re-circulating flow regions and these regions presumably provide an excellent opportunity for the injected fuel mix with the flow.
- This happens because of unsteady shredding of sheer layers of flow from the leading edge of the cavity. In the case of cavity flame holders, fuel is generally injected from the bottom of the cavity, just before the cavity directly into the supersonic flow or simultaneously in both the positions.

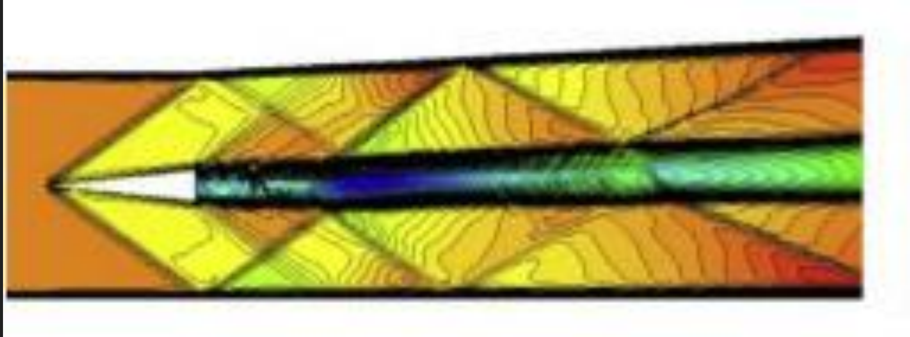
Flame Holders

<u>c. Ramp and Strut Based Injection Method:</u>

- Other methods like Ramp and Strut-based injection system a geometric object are placed with the supersonic flow. As mention before, any obstruction placed in the way of the <u>supersonic stream will cause a bow shock, which adversely affects the scramjet performance</u>. So, more aerodynamic shaped structures like Ramps or micro-vortex generators are used.
- In a Ramp-based injection system, from the leading edge of it, oblique shock waves are created which after being reflected the walls of the combustor <u>impinge upon the fuel jet</u> and <u>create strong velocity gradients</u>. These velocity gradients generate vortices and carry the fuel and mix it with the stream efficiently. Struts, like ramps, are also designed in such a way that it can create flow separations.
- <u>In the case of the ramp, flow separations take place from the corner of it; and in the case of the strut, the flow separation occurs at the downstream of the strut.</u>



Ramp Based Injection Method



Strut Based Injection Method

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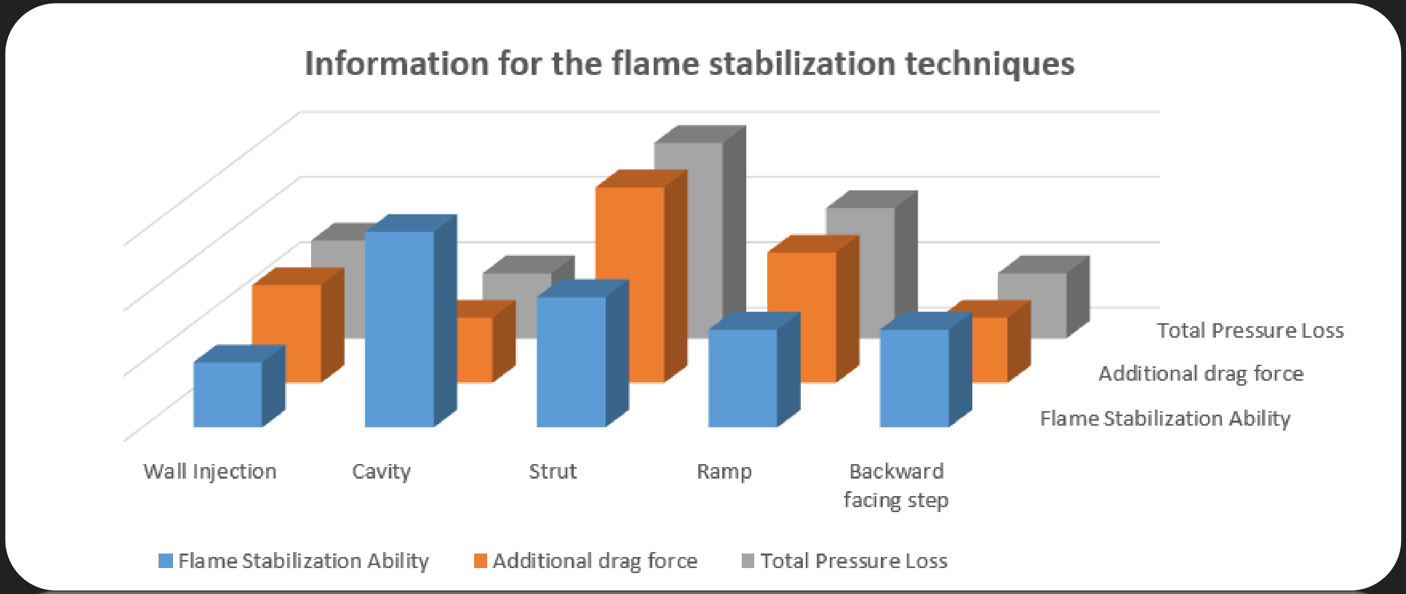
Comparison of various Flame-Holding Techniques

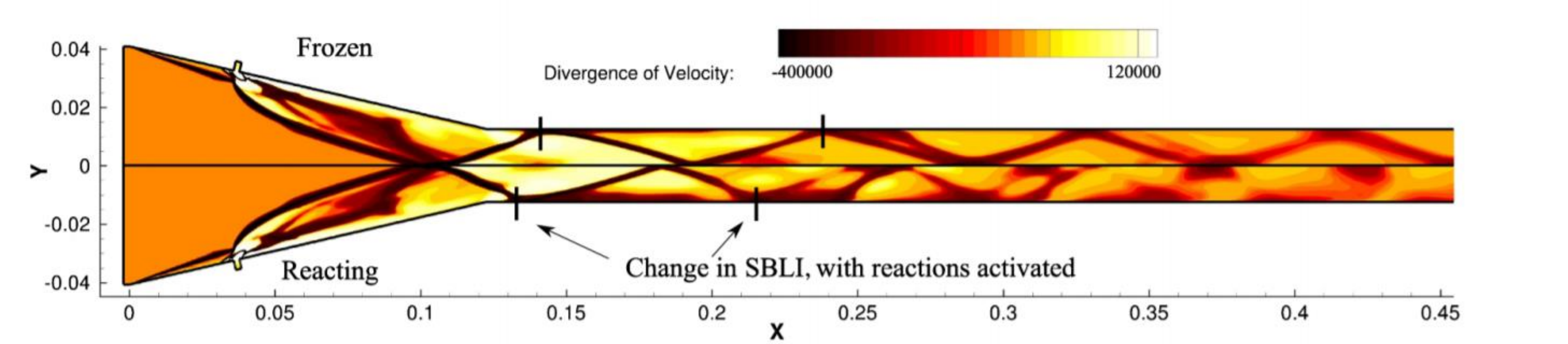


Comparison of effectiveness of various Flame-Holding Techniques

Radical Farming Based Supersonic Combustion

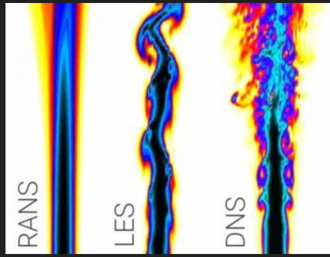
Radical Farming in Scramjet Combustor:

An innovative way of holding the flame is radical farming. In this process, high pressure and temperature regions between a shock system, termed as **hot pockets**, are generated where radicals required for ignition and combustion are extensively present. Thus, this method provides an excellent opportunity to hold the flame and achieve high combustion efficiency.

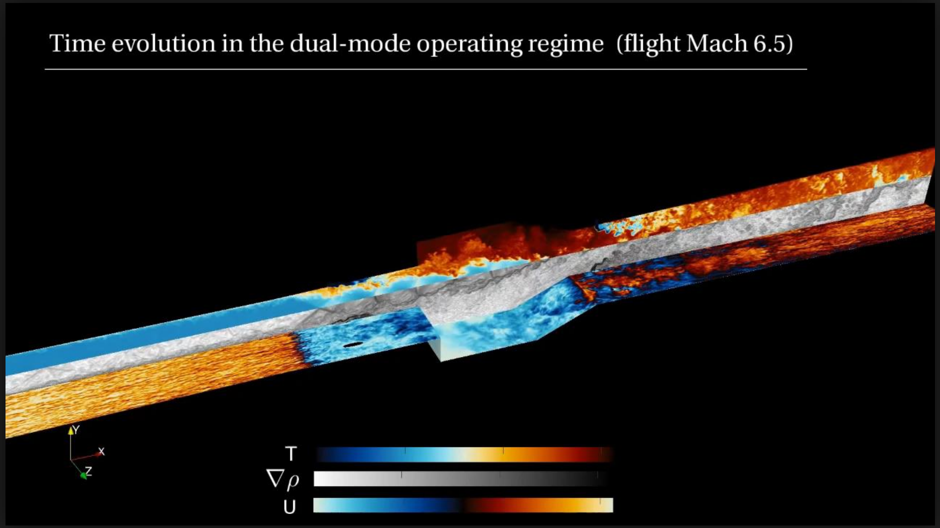


Shock Structure at symmetry plane of 2D Engine (Reacting) [6]

Role of Large Eddy Simulation in predicting Supersonic Turbulent Combustion processes



- Turbulence is always three-dimensional (3D) and unsteady with a large range of scale motions. As a result of this the primary problem with numerically computing (as well as measuring) turbulence is the enormous range of scales that must be resolved.
- The most accurate approach for simulating turbulent flows is called the direct numerical simulation (DNS) in which the full Navier–Stokes equations are numerically solved directly using very fine mesh to capture all the scales that are present in a given flow, from the smallest to the largest eddies. Therefore computationally DNS is very expensive and at present it can be applied only to low Reynolds number flows over simple geometry.
- An alternative approach is called Large-Eddy Simulations (LES) which was proposed in as early as 1963 by Smagorinsky. LES does not adopt the conventional time- or ensemble-averaging RANS approach with additional modelled transport equations being solved to obtain the so-called Reynolds Stresses resulting from the averaging process.
- In LES the large scale motions (large eddies) of turbulent flow are computed directly and only small scale (sub-grid scale (SGS)) motions are modelled, resulting in a significant reduction in computational cost compared to DNS. LES is more accurate than the RANS approach since the large eddies contain most of the turbulent energy and are responsible for most of the momentum transfer and turbulent mixing, and LES captures these eddies in full detail directly whereas they are modelled in the RANS approach.
- Furthermore the small scales tend to be more isotropic and homogeneous than the large ones, and thus modelling the SGS motions should be easier than modelling all scales within a single model as in the RANS approach. Therefore, *currently LES is the most viable/promising numerical tool for simulating realistic turbulent/transitional flows*.



Various Instantaneous contours of HLFiRE-2 Scramjet Combustor

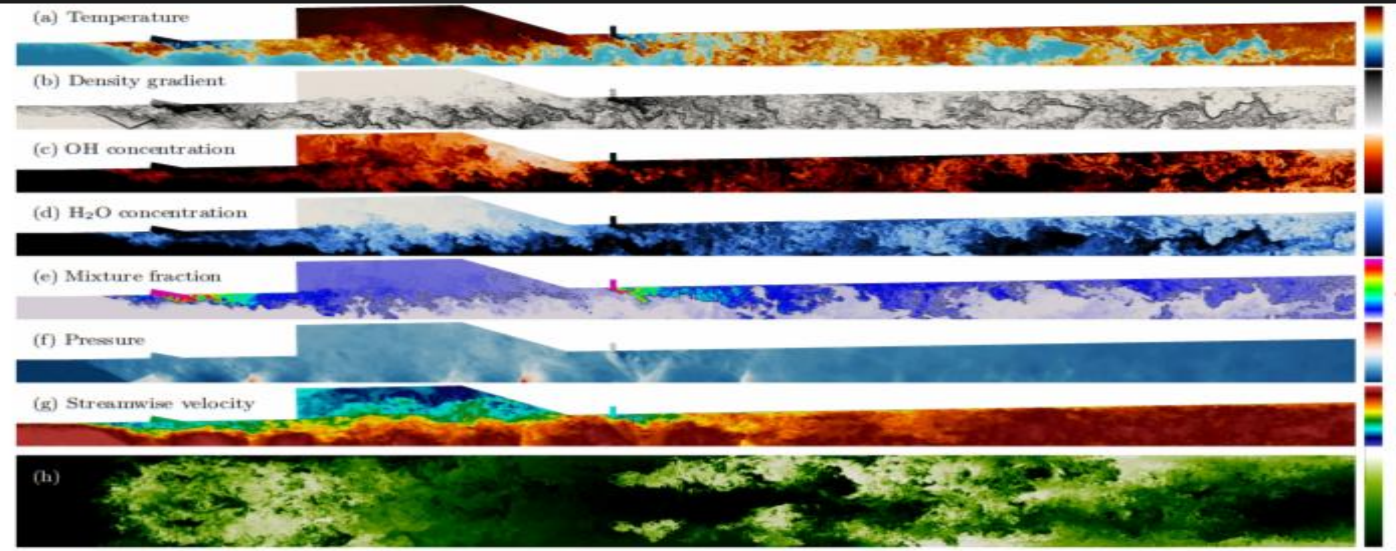


FIGURE 5. From top to bottom: contours of instantaneous temperature (215–3280 K), density gradient (15–500 kg/m^4, logscale), OH concentration (0–0.01), H_2O concentration (0–0.09), mixture fraction (0–1), pressure (77–773 KPa), streamwise velocity (-600–1615 m/s), and CO concentration (0–0.3) for the reacting-flow simulation in the dual-mode operating regime at $M_f = 6.5$. The bottom plot (h) contains a slice of the computational domain parallel to the wall of the combustor at a distance 2 mm normal to the wall. All other plots (a-g) are vertical slices at $z = 12.7$ mm passing through a set of injectors. For clarity most of the isolator has been left out of the visualization.

Wall-modeled large-eddy simulations instantaneous contours of the HIFiRE-2 scramjet.[5]

Conclusion

- The flame-holding process include the flame establishment stage, flame statbiization stage and flame extinction stage, and the flame propagation occurs in the flame establishment stage.
- The cavity has been widely employed as the flame stabilization technique in the dual-mode combustor for its potential advantages in smaller additional drag force and total pressure loss, and the formation of a large recirculation zones with low speed. At the same time, the large eddy simulation approach and the high speed schlieren photography are two common methods to investigate the flame propagation and stabilization process in the dual-mode combustor.
- The operational conditions and the geometric parameters both have a great impact on the flame propagation and stabilization process of the dual-mode scramjet combustor. At the same time, the mode transition process is very crucial for the design of the dual-mode scramjet combustor, and it should be taken into consideration seriously for the design of the hypersonic airplane in the near future.
- The optimal operational conditions, as well as the geometric parameters, should be obtained by means of the multiobjective design optimization approach, and this method has been successfully applied in the design of the components of the hypersonic airplane, i.e. combustor [171] and nozzle [172]. There exist strong interactions between the geometric parameters, as well as the operational conditions, and the surrogate model with high fidelity can be employed to solve this problem.

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