Combustion for aero-propulsion – what should you know?

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What will you expect to hear?

- **Engines intended to be designed, fuels and operating conditions**
- **Modes of combustion**
- **Describing reaction chemistry**
- **Computing combusting flows** – Ramjets, gt-afterburners, gas turbines, rocket engines, scramjets
- **Summary**

General principle of functioning

- Raise the pressure of the working fluid, (air in the case of air breathing engines and special fuels and oxidizers in the case of non-air breathing engines),
- Add heat at high pressure by combustion by adding fuels for air breathing engines, or supply the fuel and oxidizer (called propellants) pumped at high pressure into a chamber that will be at high pressure because of the C-D nozzle.
- Expand the hot and high pressure fluid through a nozzle in jet engines (including rockets) to create a high speed stream to generate thrust or additional turbine section in the case of turboprop for powering the propeller that accelerates the ambient stream to generate thrust.

More details….

- Air breathing engines for military applications are expected to have life of components in terms of several hundred to thousand hours and for civilian applications, several thousand hours.
- In missile applications rocket engines have a life of a few to several hundred seconds.
- These distinguish the demand on performance as well.

Performance aspects

- Thermodynamic analysis tells us that ***the use of higher pressures at which heat is added gives higher efficiency***.
- This is reflected in terms of a quantity called specific impulse. This term is used mostly by rocket engineers. Air breathing engine literature uses specific fuel consumption (***sfc***)
- Specific impulse is inverse of ***sfc*****.**
- Higher efficiency implies higher specific impulse of 2000 to 3000 N.s/kg for missile systems and 18000 to 50000 N.s/kg for thrust producing air breathing engines. What this implies is……..

Performance aspects

- To generate a certain thrust demanded by the vehicle, if the specific impulse is high, one needs to use a smaller kg/hr of the fuel (for air breathing engines) or propellants (for rocket engines).
- This reduction in the throughput for the same output helps make the system more compact.
- Compactness is the hall mark of aerospace systems, because it implies reduction in drag forces as the vehicle travels through the atmosphere and hence better flight performance.

Problems of high pressures

- Deploying higher pressures has its engineering related issues.
- High pressures imply higher chemical reaction rates and hence higher heat release rates.
- Also, hot fluids flowing at high pressure cause higher heat transfer to surfaces over which they are passing.
- Thermal protection systems have therefore to be in place in all propulsion systems.
- High heat release rates also lead to a coupling between acoustics and heat release that cause difficult-to-solve high frequency instabilities.

Some numbers…

- Since the performance benefit ultimately forms the key driver, other issues are solved by suitable techniques.
- Early designs adopted low pressure ratios (Pi_c) for gas turbines and low p_c for rocket engines.
- As time progressed, as a response to demand for higher performance, high pressures were deployed both in air breathing and rocket engines.
- Modern day gas turbines – turbofans have a compressor PI_c of 40. Rocket engines like the PSLV core engine or Russian engines with storable propellants (non-cryogenic propellants) use p_c of 60 to 100 atm (SSME engine used on space shuttle has a p_c of 200 atm).

Temperatures (T_c)?

- High p_c in gas turbine engines also implies higher combustion T_c arising out of optimizing the performance.
- Systems designed and produced earlier at lower compressor pressure ratios and small gas turbines even today have a turbine inlet temperature (TIT as it is denoted) that is the same as combustor outlet temperature of 1200 K and the current day TIT's have reached 1900 K with the aim of reaching 2100 K in the coming decade.
- We note that the peak adiabatic T_c of kerosene –air system is ~ 2400 K (for the gas turbine combustor e啮糗嶩▪☐We recognize that the theoretical limits are being reached in practice.
- In all these engines, one has to use turbine blade cooling along with blade coating approaches to handle the severe thermal problems.

Temperatures (T_c)?

- In rocket engines, the use of reactive propellants leads to adiabatic flame temperatures of 2600 to 3600 K.
- Raising pressures from 30 to 100 atm raises the flame temperature of a given fuel-oxidizer system at the same stoichiometry by 150 to 200 K due to reduced dissociation at higher pressures.

Features of various engines

Engine	Fuel	Oxidizer	Comb. Pr. atm	Inlet Temp., K	Peak flame Temp, K
Gas turbine main combustor	Kerosene (liquid)	Air	3 to 40	350 to 450	1200 to 1900
Gas turbine afterburner	Kerosene	Vitiated air	2 to 4	600 to 700	2100 to 2200
Liquid rocket engine	Chemicals– UDMH, Amines, etc (l)	RFNA, N_2O_4 (l)	50 to 100	240 to 320	3000 to 3600
Solid propellant engine	Polymers, Al, DBP (solid)	AP	50 to 100	240 to 320	2600 to 3600
Hybrid rocket engine	Polymers – (solid)	RFNA, N_2O_4 (l)	50 to 100	240 to 320	3000 to 3500
Scramjets	Kerosene, High density HC (l)	Air	0.5 to 1	1200	2300 to 2500

Gas Turbine and Rocket Combustors

- Work over a wide range of pressures and temperatures.
- Engines designed and developed in the sixties had a lower compressor pressure ratio and over a time the pressure ratios have increased dramatically to as high as 40, improving the overall efficiency substantially.
- They operate over a range of altitudes – up to 15 km, say, the pressures in the system vary by a factor of four.
- This is also the reason for the lowest combustor pressure to be as low as 3 atm even when it is operating at about 10 atm during take-off or landing of vehicles (with this propulsion system).
- This is not so with rocket engines whose operation is independent of the ambient conditions in so far as combustion chamber is concerned.

Gas turbine and rocket combustors

- The combustor inlet temperature in the case of gas turbines is dependent on the compressor pressure ratio.
- The compression process is close to adiabatic process and hence higher compression ratio implies higher temperature at the end of compression.
- The T_{ad} is a consequence of the combustion process at the appropriate O/F ratio.
- For gas turbines, the temperature limits posed by the turbine determine the A/F ratio.
- For rocket engines, the choice of O/F is dependent on optimizing the performance of the rocket engine in conjunction with the vehicle.

Ramjets and Afterburners

For ramjets and afterburner of gas turbines, the pressures are always relatively low, but the peak temperatures are close to stoichiometry.

Modes of combustion

- Most combustion process occurs in gaseous phase.
- When liquids or solids are used, vaporization or pyrolisis is the first step.
- In the gas phase, there are essentially two modes of combustion – diffusive and premixed.
- In the diffusive mode, mixing between fuel and oxidizer vapors will be the limiting feature for the combustion process.
- Reaction rates and hence heat release rates are comparatively large and hence, the rates of conversion will be dependent on mixing.
- In several instances, the vaporization process itself will be the limiting feature.
- Kerosene combustion in gas turbines is vaporization limited; so also bipropellant liquid rocket combustion, both of which can be analyzed as a diffusion limited process.

Modes of combustion

- Composite propellant combustion in which fuel and oxidizer are separate constitutes classical diffusive mode of combustion.
- But fine particles of ammonium perchlorate decompose and mix with the binder and this leads to premixed class of behavior over some pressure range.
- Hence AP –Polymer propellants show up a behavior that is mix of diffusion and premixed controlled aspects.

Modes of combustion

- The combustion process in a DB solid propellant is of premixed nature, because fuel and oxidizer elements are mixed on a molecular scale and the mixing process is not rate limiting. In this case, it is the rate of chemical reactions that controls the burn rate.
- Burn rate controlled by diffusive processes shows weak pressure dependence and those controlled by premixed process have stronger pressure dependence.

Describing reaction chemistry

- Reactions do not proceed in one step from reactants to products as one may presume.
- The pathways are complex and even a simple chemistry like H_2 – air reaction scheme has seven reversible reactions and seven species – H_2, O_2, OH, HO_2, H_2O, N_2, NO.
- One can simplify these to six species if NO formation is dropped.
- If C-H-N-O system is adopted as is necessary for most applications, one needs a minimum reaction set of about 30 reactions and eleven species.
- One of the key things is to describe the rate of individual reactions.

Describing reaction chemistry

- By the law of mass action,

  Reaction rate is proportional to $A_f\, p^2\, Y_o\, Y_f\, \mathit{exp}\, [- E/RT]$

  where ***E*** = Activation energy, ***R***, the universal gas constant and ***T*** is the temperature.

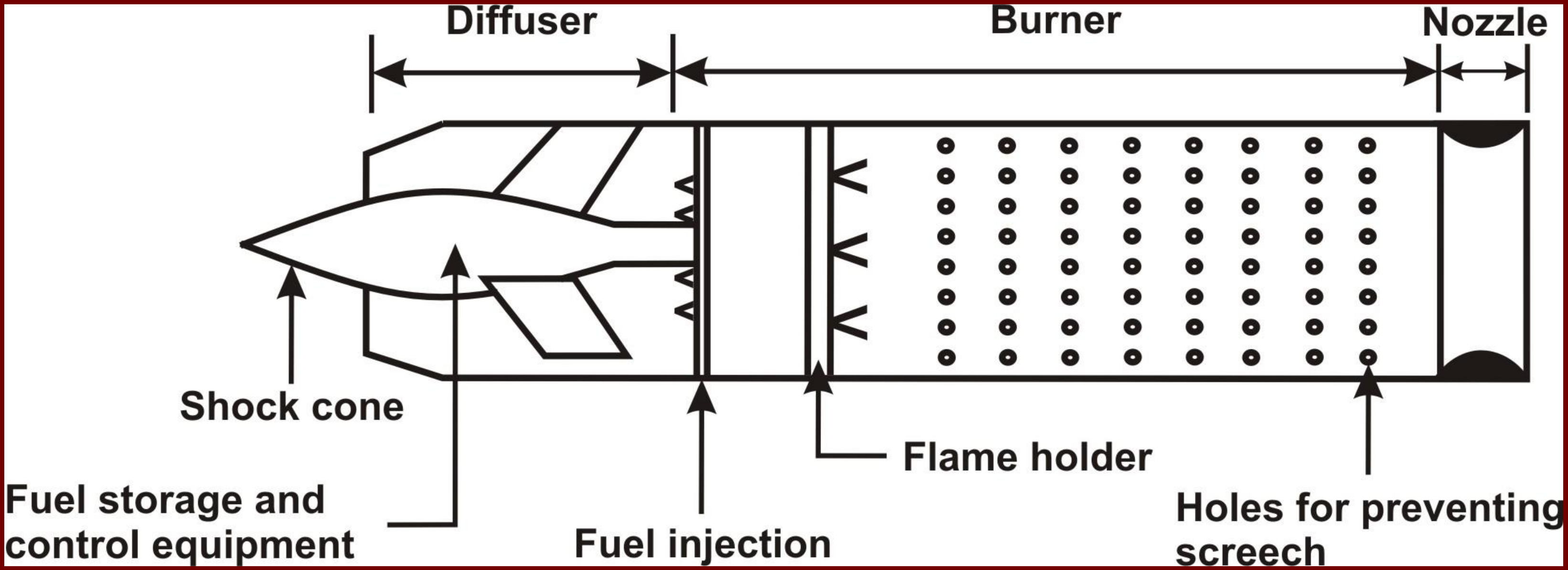
  The quantity *E/RT* is called activation parameter.
- Two quantities not known accurately are the pre-exponential constant and the activation energy.
- When one is interested in heat release distribution, it may be adequate to take an equivalent single step reaction.
- In some cases, one needs to use a two or three step heat mechanism to enable better description of heat release pattern.

Computing combusting flows

- Computing reacting flows is more complex and time consuming than non-reacting flows.
- The number of variables to be computed is enhanced by the number of species to be accounted and
- The non-linear chemistry term that has sharp variations – the zones of combustion are very thin because the operating conditions lead to high heat release rates.
- Precisely because of this, in some approximations, one uses a thin-flame approach in which an ideal thin zone in which one has reactants on one side and products on the other is also adopted.
- It is not that computation offers any great simplicity; but the time it takes to compute specific problems is made simpler.

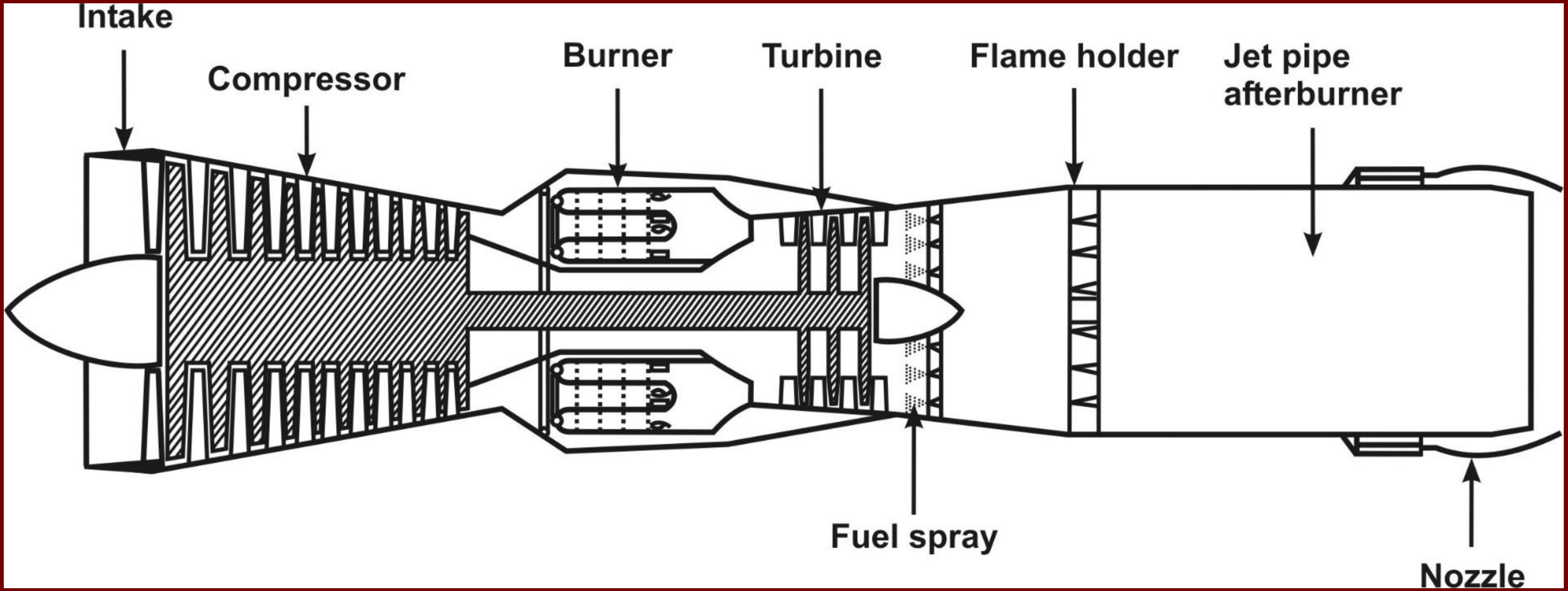
- The nest step is to treat a single step chemistry. The choice of the A_f and E are very important and care needs to be exercised in this choice. Validation is important in these cases.
- Different levels of accuracies need to be aimed at in different cases. We will examine these in the case of each of the engines.

Ramjet

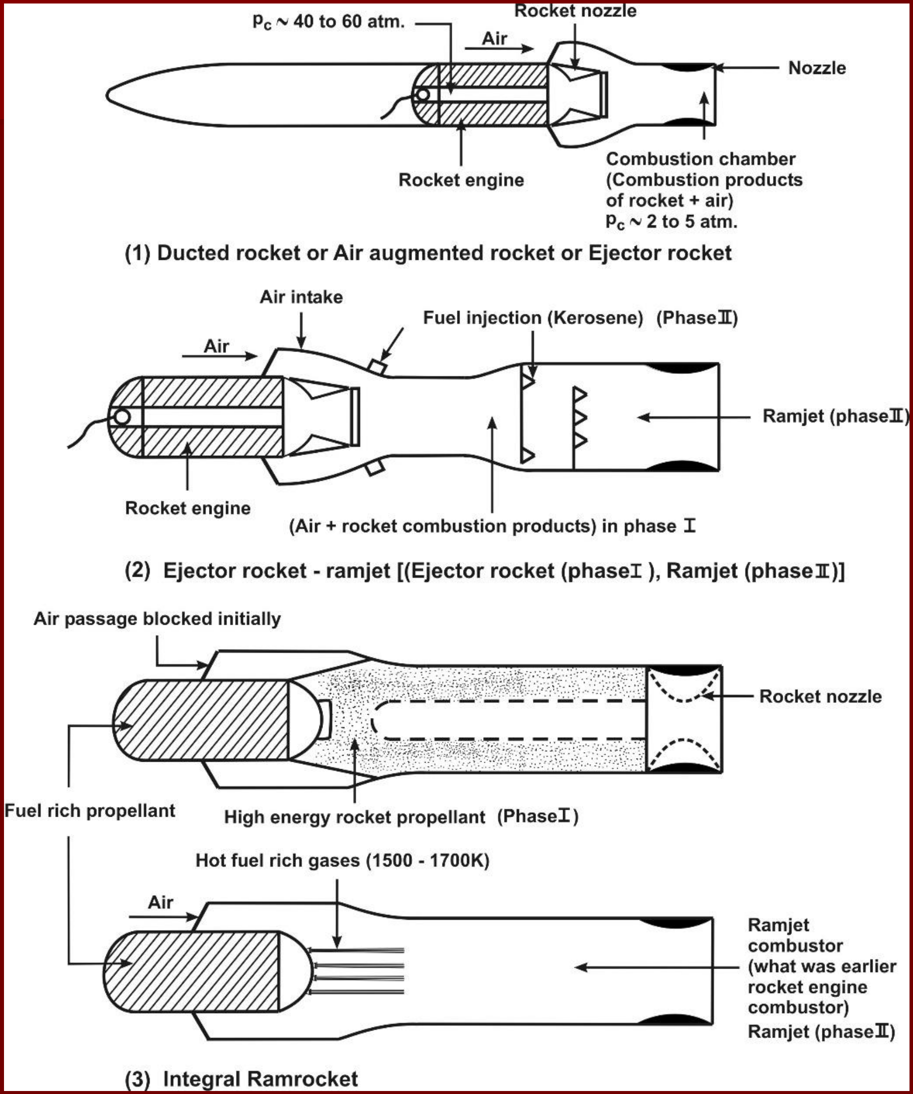


Diffuser
Burner
Nozzle
Shock cone
Fuel storage and control equipment
Fuel injection
Flame holder
Holes for preventing screech

GT Afterburner



Solid fuel Ramjets



Ramjets

- Ramjets function efficiently only at supersonic flight conditions, at flight Mach numbers of 2.5 to 3.
- The inflow is decelerated to subsonic conditions through air intakes and the air is introduced (dumped is a crude, but truthful word for that) into the combustion chamber in part symmetric or asymmetric conditions.
- The Mach number at the entry to the combustor will be 0.2 to 0.3 and the temperature is about 450 to 550 K.
- In liquid fuel ramjets, liquid fuel is injected in the form of fine sprays over the cross section through struts into the air stream and ignited so that the combustion process is completed in the combustion chamber.
- A separate set of struts are provided to act as flame holders.
- A convergent-divergent nozzle at the exit of the combustor accelerates the fluid to supersonic conditions and this produces the thrust.
- In a solid fuel ramjet, combustion of the solid fuel occurs in a chamber from which hot fuel gas jets issue into the main combustion chamber.
- Here they mix with the air from the air intake and ignite because of the temperatures involved. No separate flame holding is required.

Ramjets - analysis

- In analyzing the performance of a ramjet, it is adequate to use a cycle analysis treating the property (pressure, Mach number, and Temperature) at each point – inlet, exit of the diffuser and inlet to the combustion chamber, exit of the combustion chamber and inlet to the nozzle and the exit of the nozzle as a variable for performance evaluation.
- Ground tests will help determine any lacunae in performance – usually reduction of combustion efficiency, or a local hot spot.
- Usually an examination by the design team and some intuitive analysis allows corrections to be made to the hardware and next test follows.
- A couple of tests may be adequate to obtain the features of the hardware that is acceptable to the project team from the point of view of combustion.
- Many successful designs were built by this approach over the last fifty years.

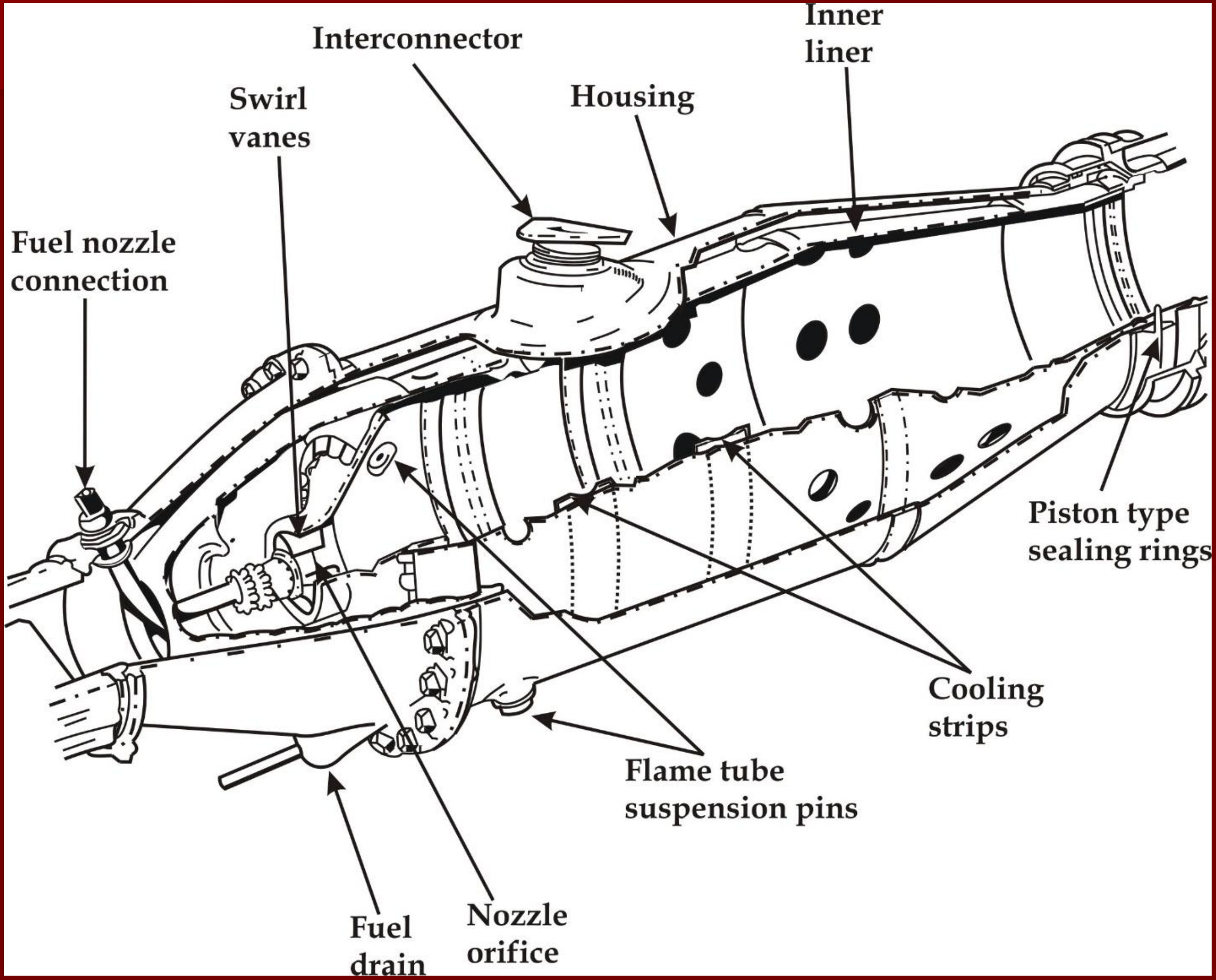
Ramjets - analysis

- In the recent past, several investigators have done a CFD study on this system.
- The non-uniformity that arises at the section where the air flow is introduced into the combustion chamber usually in a part-symmetric manner comes down in a distance of 3 D_c (D_c = combustor flow diameter) without combustion and about 5 D_c with combustion.
- The non-uniformity is not a major problem and is lived with. The reduction in performance is usually due to spray being coarse or distribution inadequate.
- Both are amenable to intuitive understanding which is deployed with ease.
- Even when the problem is not licked in the first few tests, doing a few more is usually not expensive or difficult and hence is done.
- In ramjets, therefore RCFD may turn out to be considered a luxury by the development team with some justification and hence, is usually an area for Ph. D students!

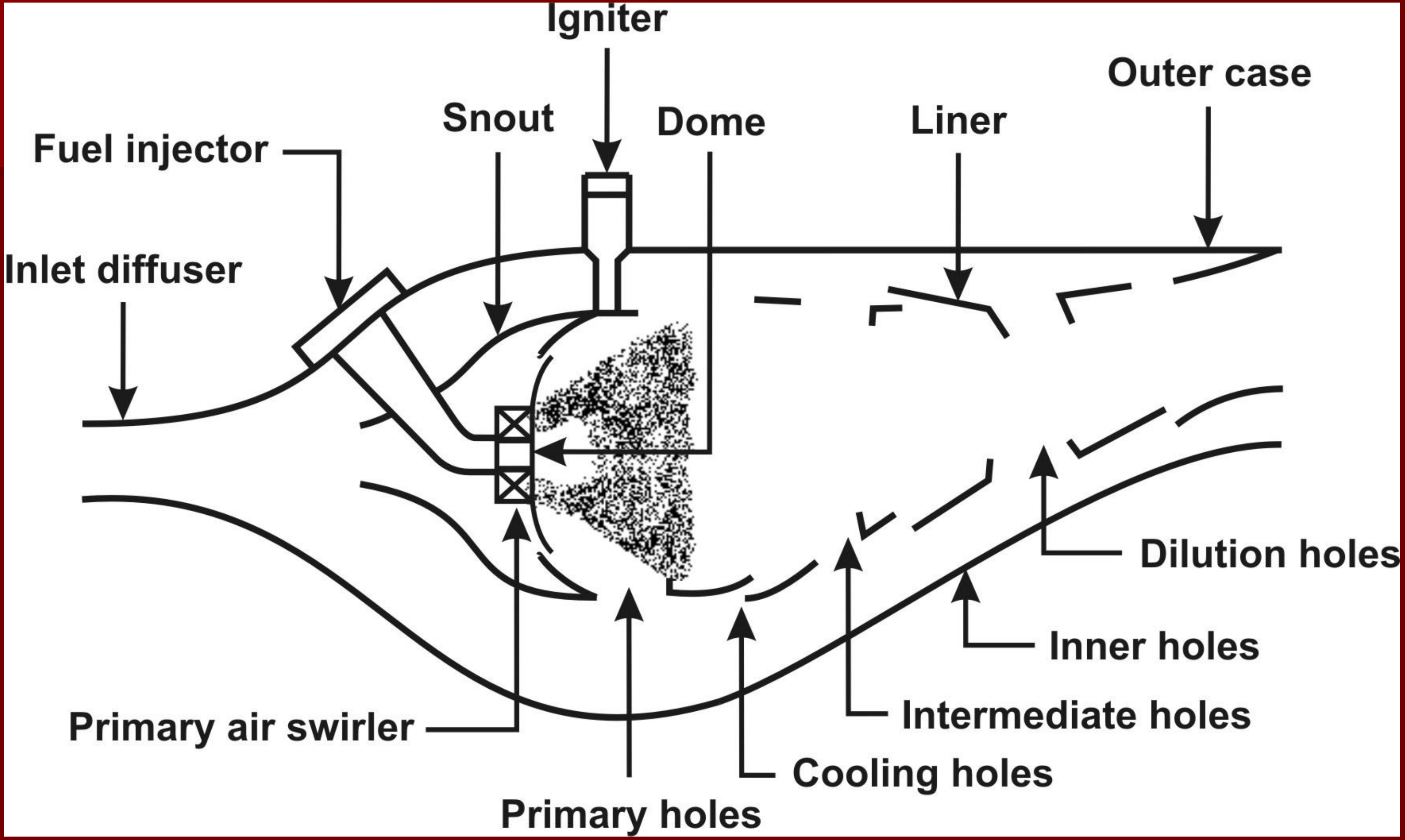
GT Afterburners - analysis

- After-burners are combustion chambers similar to ramjets.
- The inflow is a hot vitiated air stream from the turbine exit at temperatures of about 600 to 700 K with non-uniformities including swirl in the flow.
- Issues of development are similar to those of ramjets.
- One problem that affects both the devices is the high frequency instability – also called screech.
- The problem is far less severe compared to liquid rocket engines.
- A standard way of solving the problem is to provide a perforated sheet all through the combustion chamber, with the holes on the sheet tuned to absorb the energy in the frequency range around which the instability is experienced.
- This frequency can also be estimated easily from the acoustics of the combustion chamber.
- This problem is also amenable to modern day CFD analysis of acoustics but may prove an overburden to a community of intuitive experts.

GT Main combustor



GT Main combustor



GT Main combustor

- Gas turbine main combustor is an incredibly more complex device.
- It burns mixtures outside the flammability limit producing a not-too peaky temperature profile at the exit of the combustor (this desirable lack of peaky profile characterized by the smallness of a quantity called temperature quality factor),
- There should be no hot spots on the metal surface to ensure long life,
- The emissions of smoke or soot, CO, and NOx must be limited.
- All these are part of an incredibly tall order.
- Predictions of emissions relevant only in the case of air breathing engines meant for civilian applications need a more careful accounting for chemistry. One can also develop simpler procedures for obtaining fuel rich and fuel lean zones using mixture fraction approach that does not involve chemistry.

GT Main combustor - analysis

- The geometry of the combustor is also complex, some times with little space between the compressor and turbine to accommodate an in-line combustor (in which case, one uses a reverse flow combustor).
- Typical cycle time for the development of a satisfactory combustor used to be 60 months thirty years ago and it has become 18 months in the last few years.
- This incredible development has happened largely because of RCFD and computational speed.
- Thirty years ago, there used to be rig tests on part combustion chambers with at least ten major modifications over several cycles.
- In recent times, there have been changes. The design starts a RCFD investigation for a new design in the back drop of a historical record of problems and solutions for several engines documented well.
- After four months of RCFD runs and discussions, and modifications, a single hardware is built and test run.
- Only in one out of three cases would one need to create a different model for a rig and test run the system.
- It is being anticipated that the cycle time from specification to realization will be brought down to 12 months. This remarkable achievement is one of the primary motivations for all of you to learn the fundamental physics and the tools of RCFD.

GT Main combustor - analysis

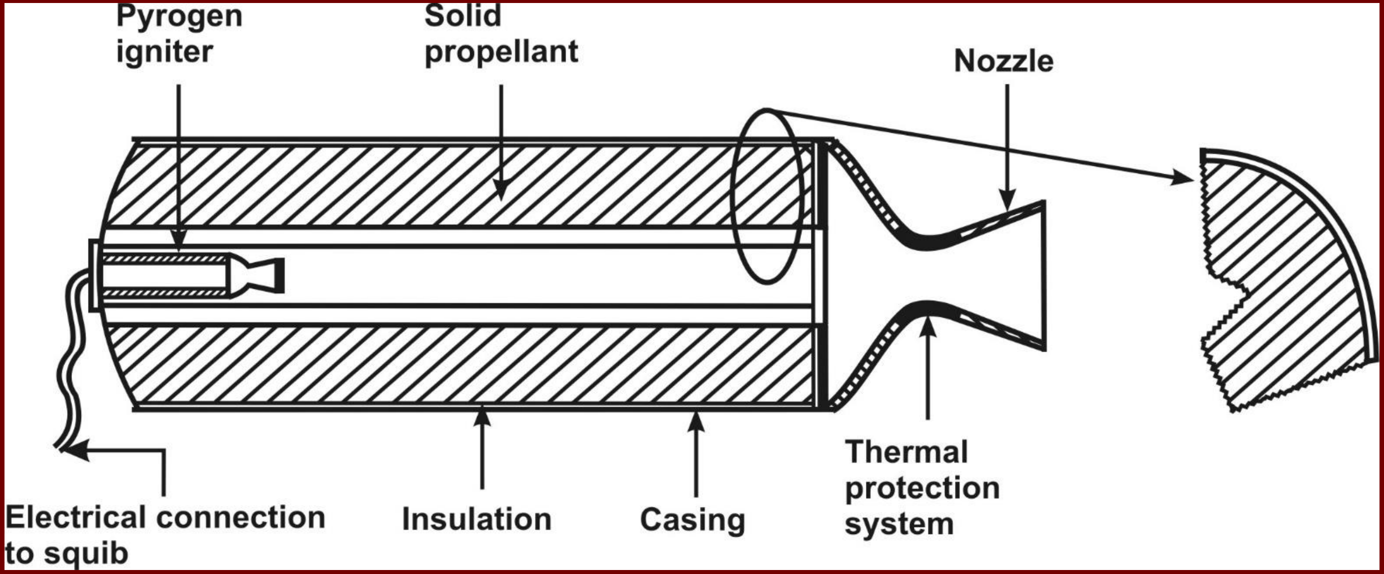
- I have indicated fundamental physics also has to be understood.
- You might ask, why? Since all the knowledge has been set out into the codes in some form or the other, would it not be sufficient to understand RCFD and manage.
- Take reaction chemistry, for instance. It is a developing field. The code writers would hardwire some data into the system at some point of time. Subsequent to this, the data set would have changed due to natural developments.
- If you do not keep track of these developments, you would produce results from your code that might be spurious. There are also areas in which developments have got saturated at an incorrect position due to lack of further interest in the subject.
- If some body does research now and refines the data, the picture that emerges from a study using the new data could be vastly different.

GT Main combustor - analysis

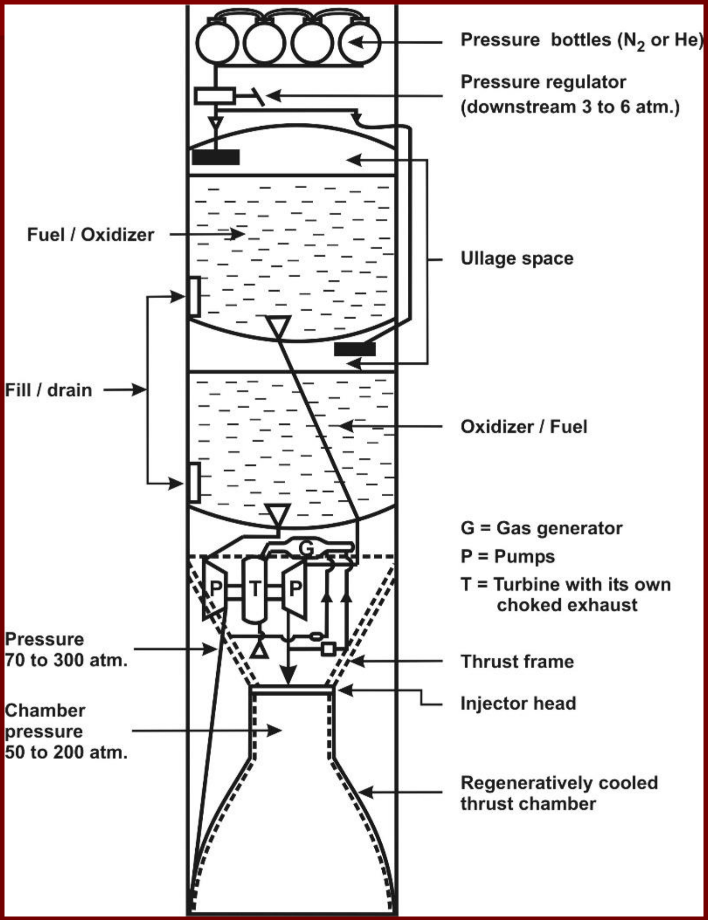
- Quite often, one would give respect to printed word, some more than the others.
- After all in developing literature, one would find that what was said yesterday could be altered today. One should also remember that what is said today can be altered tomorrow.
- Hence one should be circumspect and evaluate the available evidence to determine how much of the known can be accepted as relevant and applicable in practical circumstances.

- While it is clear that the RCFD tools are extensively used in all advanced aerospace companies overseas, our country has lagged behind very significantly, almost by design it appears – attempts to collaborate with them even as early as 1978 were rebuffed (not even politely and even after there was blessings from the head!).

Solid Rocket Motor



Liquid Rocket Engine



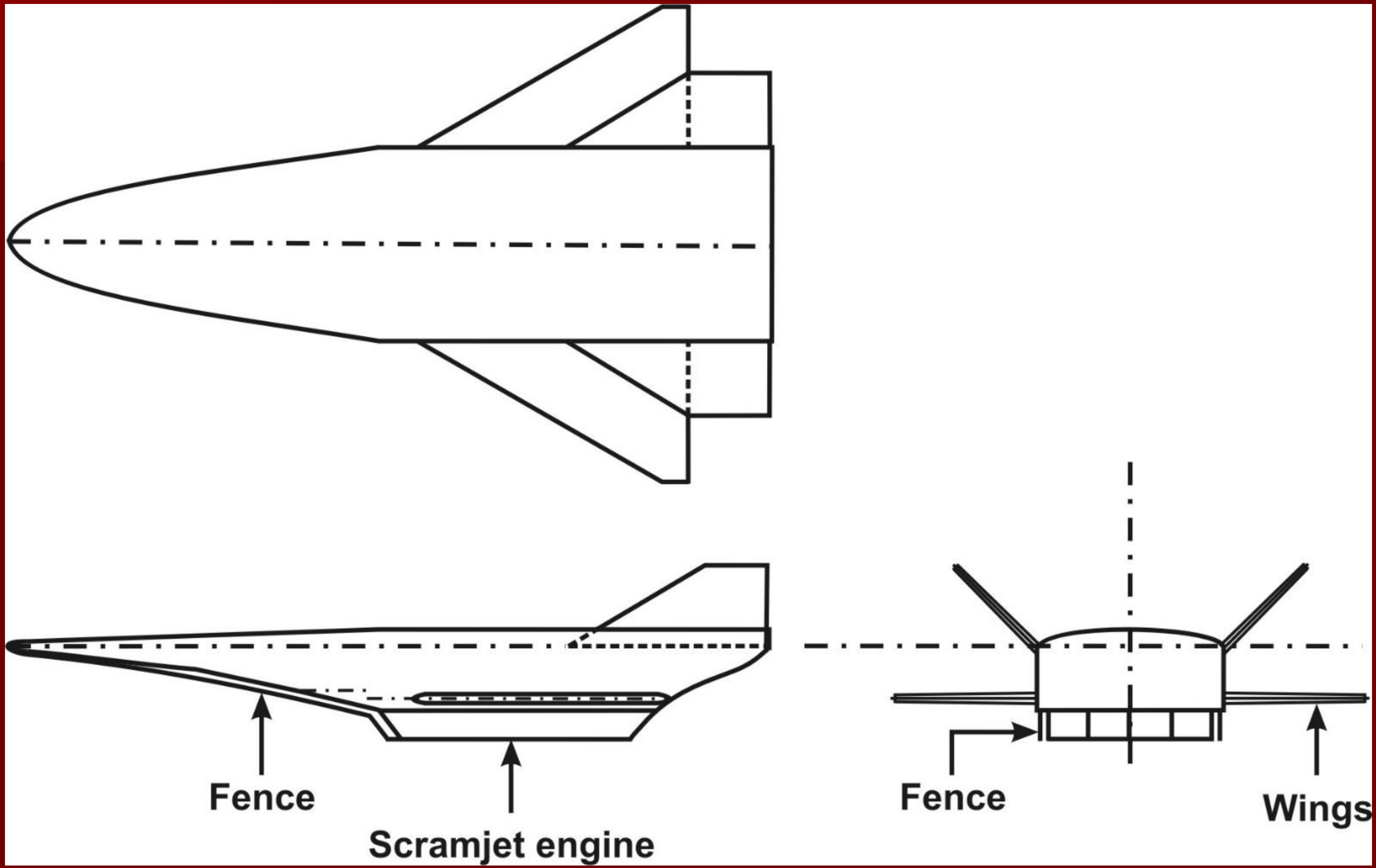
Rocket Engines

- Most early developments were carried out without depending on CFD tools.
- By 1970, most critical developments had been completed.
- It was only the SSME main liquid cryo-engine that got completed in an era (1980 – 85) when computational tools were gaining recognition in rocket engine industry as a useful tool.
- The vibrations felt in the injector assembly were analyzed by fluid dynamic tools and were eliminated.
- The RCFD tools are used these days extensively for more precise understanding of the flow behavior and improving intuitive skills by understanding the intricacies of the flow structure.
- The design of turbo pumps and the turbines can be carried out through CFD to improve the efficiencies of operation.
- Considerable effort into understanding the combustion behavior of solid propellants, both composite and double base, is a current area of research both in India and overseas.

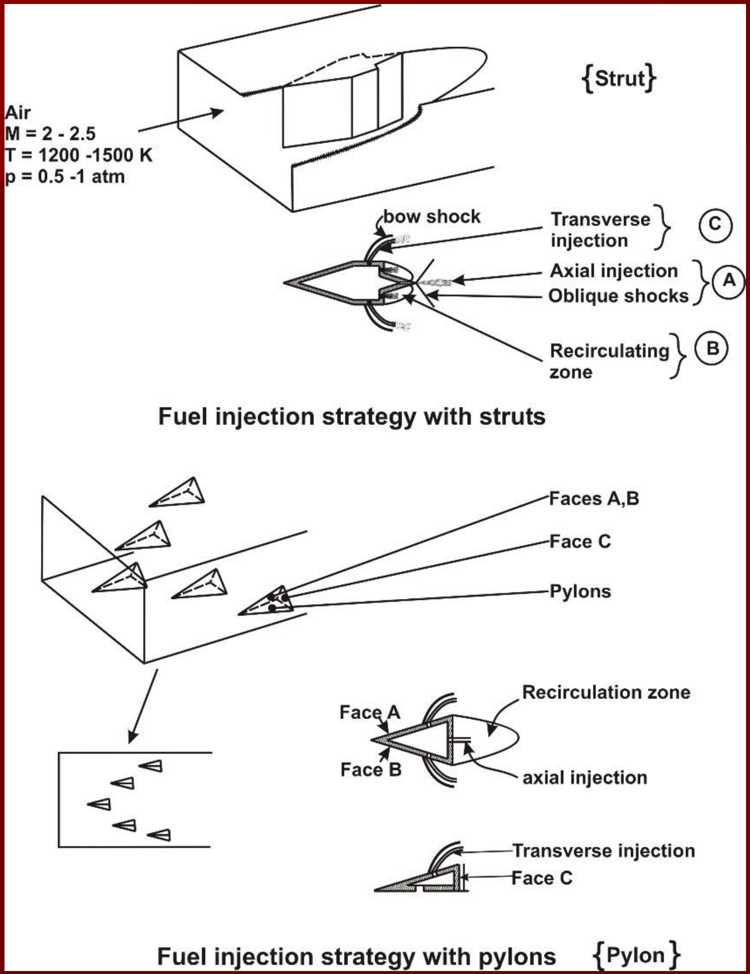
Rocket Engines

- If one were ask whether the performance of a rocket engine can be enhanced substantially by the use of CFD tools, the answer is not in the affirmative, for whether it is solid rocket motors or liquid rocket engines, the contribution is not visibly high excepting in the area of high frequency instability where RCFD is being brought in to understand intricacies of acoustics – flow field interactions responsible for instabilities.
- This feature must be tempered by the fact that very few new designs are being sought by the armed forces in advanced countries.

Scramjet



Scramjet engine



Scramjets

- Scramjet engines are expected to work at flight M ~ 7 to 10.
- At these Mach numbers that reducing the Mach numbers to subsonic conditions will lead to serious stagnation pressure losses and the stagnation temperatures are so high (2000 to 2700 K) that the possible marginal heat addition will not help create useful thrust.
- Hence, the flow is decelerated to low supersonic Mach numbers, typically one third the flight M (or slightly more) and combustion process initiated at these conditions.
- Typical static temperatures will be about 1200 to 1600 K and pressures about 0.5 to 0.75 atm.
- While the high static temperatures are satisfactory for ignition, certainly of hydrogen fuel and perhaps even of hydrogen gas induced liquid hydrocarbon fuel sprays, the low pressures may demand larger combustion volume, a feature that may be critical for the design of hypersonic vehicle propelled by a scramjet.

Scramjet

- Fuel needs to be injected into the combustor that has supersonic flow inside with large enough static temperatures, and much larger stagnation temperatures.
- Avoidance of hot pockets near the walls implies that the fuel be injected from centrally located struts.
- The usual circular configuration for combustors can be sacrificed in favor of a rectangular configuration.
- Typical velocities in the combustion chamber are about 1 to 1.5 km/s and the Mach numbers will be 1.4 to 2.3 for a typical combustor entry Mach number of 2.5.

Scramjets

- Local heat release leads to enhanced temperatures.
- This increase causes increased acoustic velocity (~ √ T) and reduction in Mach number even if the local speed is unaltered.
- One can expect a non-uniform temperature distribution since the fuel sprays are introduced over parts of the cross section.
- This leads to non-uniformity in other quantities as well.
- Even the pressures are not uniform since local shocks can create the mechanism for sustaining the pressure changes.
- The last feature is unlike subsonic flows where non-uniformity in temperature does not mean non-uniformity in pressure.

Scramjets

- The inflow into the combustion system comes from an air intake that begins from the nose of the vehicle and decelerates through a series of shocks from the changes in the surface at the bottom of the vehicle that would be inherently non-uniform.
- In view of these features, the flow through the rectangular intake will be three-dimensional.
- Many geometric features like a step or a protrusion, wanted or unwanted will all make a significant difference to the flow field.
- The flow field over the vehicle at M = 10 would be reactive – significant dissociation of the air stream would take place.

Scramjets

- Enthalpy turns out to be more relevant parameter; At lower Mach numbers, enthalpies and temperatures have synonymous meanings.
- At the high enthalpies, significant dissociation occurs with addition of heat or passage of the fluid through a shock.
- Hence RCFD is very critical to the understanding and the design of the system.
- Whatever subsidiary aerodynamic or thermodynamic data that would be required for design on the computer could be obtained from separate experiments in hypersonic tunnels and shock tunnels.
- RCFD is so critical that contemplating the design without CFD tools would be just impossible.

Scramjets

- One would plan to fly the vehicle on a computer before contemplating initiating the fabrication activities.
- Hypersonic propulsion could not have been built in an era where RCFD tools could not be used.
- In fact, only some less than satisfactory experiments have been made and a vehicle that flies hypersonically on supersonic propulsion system has not been built in the World till today.

Summary

- Vehicles flying inside the atmosphere for long durations – like military aircraft have one kind of demand on optimization.
- Minimizing the drag, having enough thrust power for maneuverability, and quick dash are related demands on propulsion.
- Those vehicles which fly with for much shorter durations – typically in tens of seconds to the maximum of a few minutes instead of hours generally operate at supersonic speeds some times outside the atmosphere as well. Aerodynamic considerations are different.
- Some propulsion systems can be designed with cycle analysis and one-dimensional treatments and intuitive understanding of the physics and chemistry of the flow.

Summary

- The design of gas turbine main combustor requires RCFD tools if one has to reduce the time scale of realization of the engine to modern day expectations.
- Hypersonic propulsion system can simply not be designed or realized unless RCFD tools are utilized.
- Utilizing these tools that have a substantial validity, but improving on many aspects on a continuous basis through the use of more advanced physics demand that the user be aware of the developing situation.
- This effort requires that the users, implying most of you, need to know the associated physics too.